BAUSCH & LOMB UNIVERSAL STAGE ON THEIR MICROSCOPE

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The Universal Stage
(With five axes of rotation)

BY

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Preface

THE universal stage is beginning to receive in America the attention which is due so powerful an instrument. This growing interest of American petrographers has inspired the discussion offered here since at the time of writing there is no unified account in English of the uses and varied applications of the instrument. I am limiting my subject matter to the bare essentials of theory and I am emphasizing the practical application of the universal stage to everyday petrographic problems. Further I am treating only the universal stage with five instead of four axes of rotation in recognition of the evident reluctance of the average American petrographer to use the stage with four axes of rotation except in the limited study of uniaxial crystals.

Although the better modern petrographic microscopes do not contain Nicol prisms, the term has become virtually synonymous with polarizing prism. Accordingly, the polarizing prisms are referred to throughout as "nicols"—"polarizer" or "analyzer."

I assume a knowledge such as the geologist possesses after an elementary course in petrography. However, since the principles of crystal optics as ordinarily taught do not stress those aspects of the subject on which universal stage procedure is mainly based, there is included here a brief review (Chapter 1) of those principles most needed in this work.

Search for liquids to be used in the double variation procedure has been spread over 12 years. Many liquids have been tried for a year or two in the student mineral laboratory at the University of Wisconsin and then rejected. Though the set of liquids given here is eminently satisfactory even to a critical eye, nevertheless changes may be expected if superior liquids are found, though the search is not now being pressed. The present set of liquids differs very much from the set which I originally published in 1929 in the American Mineralogist. During this long search I have received very real aid, most unstintingly given by C. W. Muehlberger, Ph.D., toxicologist, Cook County Coroner's Laboratory, Chicago, Illinois. He has personally prepared many organic liquids, unrecorded in standard references, and unlisted on the market but conceived by him as promising for theoretical reasons. Some of the best liquids in the present list, now made by Eastman Kodak Company, were discovered in this way. It would have been impossible to arrive at the present satisfactory set of liquids without his detailed co-operation.

I am indebted to Dr. T. A. Dodge, who kindly loaned me his original drawings from which Figures 11–16, inclusive, were made. These curves were developed for his master's dissertation when he was a graduate student at the University of Wisconsin.

A large part of this manuscript has been used by my students during the past several years in the mineral laboratory of the University of Wisconsin. I have benefited by their helpful criticism and suggestions.

The concept of the wave surface has been retained in Chapter 1 contrary to the friendly advice of Prof. E. S. Larsen. It has been retained in the belief that the wave surface model of Figure 1 aids the beginner in visualizing the results of the mechanical rotations of the universal stage.

In the illustrations all stated magnifications are ocular times objective and do not take into consideration the magnification added by the camera nor the reduction in producing the cuts.

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Introduction

THE universal stage is undoubtedly the petrographer's most powerful accessory. It not only increases greatly the effectiveness of the petrographic microscope but conserves the petrographer's time in all but the most routine examinations. Current literature constantly stresses the ever-increasing importance of learning more about the specific characteristics of crystals—characteristics which reveal facts that cannot be learned by a cursory examination.

The requirements for a suitable determinative technique are becoming more pressing and more clearly defined, especially as our knowledge increases in the field of correlation of optical constants and chemical composition of crystalline materials. Workers in the allied sciences who are beginning to show interest in determinative optical technique with a view to using it in their own work commonly find that the inaccurate routine procedure renders the results somewhat intangible. They are not satisfied with an indefinite statement corresponding with our "olivine," "scapolite," or "epidote," or, to name one of our best, "plagioclase $(ab_{70}an_{30} \pm 5\%an)$." Nor are the mineralogists remaining satisfied with this type of determination. We are requiring more specific information, particularly in the chemistry of the materials we are handling. Although suitable data for our newer needs are not yet available they are accumulating. To use such data necessitates rapid accurate determination not only of the three indices α, β, and γ but also of any other conveniently available constants. To determine the three indices accurately it is necessary to go through most of the steps necessary to secure other data of important critical value such as dispersion and crystallographic orientation. It seems fair to assume that, as index data of accuracy $\pm.003$ and $\pm.001$ have accumulated in the past so also will data of accuracy $\pm.0004$ and $\pm.0002$ be accumulated in the future.[1] The value to the research worker of suitably accurate data can scarcely be overestimated. Although we cannot yet determine optically with satisfactory accuracy the three main constituents (ab, an, or) of feldspar, our most common mineral, yet preliminary calculations suggest that we will meet this limitation when index data correct to $\pm.0002$ are properly correlated with analyzed material. Probably, however, stereographic projections such as those of Duparc and Reinhard (1924) will be an essential accessory, indicating changes in the relative orientation of ele-

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[1] Reference is made to Barnes (1930), who records 369 mineral index determinations of which 63 are $\pm.0002$, 27 $\pm.0003$, 81 $\pm.0004$, 144 $\pm.0005$, and 54 are of greater error, the maximum being $\pm.0012$; the size of the error is closely related to the color of the material in this case. Some of the material was so strongly absorptive as to be almost opaque except in very minute grains indeed.

ments of optical symmetry with respect to crystallographic directions. Other minerals than feldspar will in turn doubtless demand an equally rigorous procedure for their complete understanding. The successful attainment of these worthy objectives will be realized only through the co-operative research efforts of a large number of workers actively interested in the detailed study of crystalline materials.

A rough approximation of the mean refractive index of a crystal may be obtained by making two or three or more liquid mounts in the routine manner. Until recently that has been adequate for our needs, but the diagrams of Winchell and others which correlate the more detailed optical properties with composition expand our interpretation and demand greater accuracy and detail. In this the universal stage finds its greatest usefulness. In determining refractive indices, for instance, the uncertainty about orientation is positively dispelled, without the laborious search for a centered interference figure, which search may be extremely tantalizing if the crystal being studied has a marked cleavage. The universal stage eliminates these difficulties by making it possible to select any convenient crystal, orient it, and determine its properties. Further, the statistical procedure introduces another inestimable error in that the index determinations for α, β, and γ are not all made *on one grain* as they are on the universal stage. In particular the operator of the universal stage is confident and satisfied with his determinations when the possible variations are properly controlled. In my judgment this confidence is essential, especially to the research worker; the absence of it undermines subsequent conclusions.

The early applications of the universal stage dealt exclusively with feldspar determinations, which has led to a common belief that it may not be used for other purposes. In the mineral laboratories at Wisconsin feldspar studies on the universal stage are no more frequent in proportion to other crystals than in routine petrography—or possibly less so since we are inclined to determine feldspars by the method of Tsuboi except for special purposes or if thin sections are used.

Those who have not attempted to use the universal stage may believe it to be complex and cumbersome. Such a belief, if justified, is adequate reason to follow other methods. The concept is, however, doubtless to be attributed to descriptions of the Fedorow stage with four axes of rotation. Paradoxical though it may at first seem, the stage with five axes of rotation is not cumbersome since no graphical construction is required to orient a crystal. It is simple in that its operation depends on a very few concepts of crystal optics, well known to all familiar with the petrographic microscope. The opposing mis-

conception amounts to a prejudice, even to a barrier, to the fruitful use of the universal stage, and though thoroughly unjustified it is extremely difficult to dispel prior to actual trial with the instrument. *In the following pages, the discussion is restricted exclusively to the universal stage with five axes of rotation.*

Chapter 1
Some Pertinent Fundamental Concepts of Crystal Optics

THIS review covers mainly those points which general experience has indicated need added emphasis prior to introducing the universal stage.

Isotropic Substances have for their wave surface, a sphere. Light vibrates with equal facility in all directions, is propagated with equal velocity, and has therefore one value of refractive index for all directions of transmission for one wave length of light and at one temperature. Therefore, a suitable immersion medium is isotropic, glass when unstrained is isotropic, and isometric crystals are isotropic in general. Such substances are the simplest to understand and to study, but their very simplicity sometimes renders them difficult to determine because of lack of varied critical data.

When light enters such an isotropic substance, its velocity alone is affected—disregarding, of course, surface influences. Especially, the vibration direction is not changed. If the substance, then, is rotated about any axis whatever passing through it, still the vibration direction is not changed, nor is the velocity of light, nor its refractive index. For such substances the universal stage is of no help. The procedures recommended in the following pages provide for simpler and more expedient methods.

Anisotropic Substances are divided into two groups according to whether there is one or two directions (optic axes) in which light is propagated as in isotropic media. They are further divided into positive and negative according to the relative velocities of the transmitted rays. Such substances comprise the other five crystal systems.

Uniaxial Crystals have one optic axis direction. In all other directions within a uniaxial crystal, light is propagated as two rays of different velocities, one of which is constant in velocity and refractive index and has a spherical wave surface. For this ray all directions of transmission of light yield but one value of refractive index, and, therefore, there is no change in this refractive index on rotation. It is known as the *ordinary ray*. The second ray (known as the *extraordinary ray*) does not have a constant velocity and must be studied with the orientation of the crystal in mind.

In the direction of the optic axis there is but one ray—that is, the rays have equal velocities. In all other directions the velocity and refractive index of the second ray are different, the difference increas-

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ing as the transmission direction makes a greater angle with the optic axis. The difference is constant for all positions in which this angle has a fixed value and reaches a maximum when this angle is 90°. The wave surface of the extraordinary ray is an ellipsoid of revolution which is tangent to the sphere at the optic axis. If the wave surface of the extraordinary ray is within the sphere the crystal is termed positive, if outside the sphere it is termed negative. In a positive uniaxial crystal, therefore, the refractive index of the extraordinary ray is greater than that of the ordinary ray; in a negative uniaxial crystal the refractive index of the extraordinary ray is less than that of the ordinary ray. The importance of orientation is apparent then in the study of such a crystal, since under the microscope orientation determines the transmission direction. Although any known orientation yields information which may be used it is convenient to obtain a "critical orientation" for determinative purposes. The refractive index of the extraordinary ray is given for statistical purposes as the extreme value relative to that of the ordinary ray—that is, when the transmission direction of light is 90° to the optic axis.

It is essential to the practical understanding of optical crystallography to emphasize the vibration directions of transmitted rays rather than the transmission directions. Tunell (1933) gives a clear, nontechnical statement of principles, with further references. Since light rays vibrate perpendicularly (or nearly so) to their transmission directions we may define the vibration adequately by referring to the *plane* of vibration and the transmission direction within it.

The plane of vibration of the extraordinary ray always includes the optic axis of the crystal. The vibration direction of the ordinary ray is perpendicular to this and to the transmission direction. The vibration direction of the extraordinary ray coincides with the optic axis, then, only when the transmission direction (the axis of the microscope) is perpendicular to the optic axis. Under this condition, only, is the critical value of the refractive index of the extraordinary ray available to direct measurement though it may be calculated or determined graphically from data on other known orientations.

A uniaxial crystal mounted for microscope study so that the optic axis is parallel to the axis of the microscope (which we shall assume to be vertical) appears isotropic—all the transmitted light vibrates perpendicularly to the optic axis and has the refractive index of the ordinary ray (ω). It is true also when the crystal is rotated in polarized light on the microscope stage. If, however, the crystal is rotated on a horizontal axis a few degrees, then the optic axis becomes inclined, and the crystal appears doubly refracting. One ray vibrates

in the plane which includes the optic axis, the other perpendicularly to it. The refractive index of the first ray (extraordinary) has changed, down if the crystal is negative, up if it is postitive, whereas the index of the ordinary ray is unchanged. On further rotation about the horizontal axis the vibration directions remain relatively the same, the index of the ordinary ray remains constant, and that of the extraordinary ray changes progressively to a maximum difference from the index of the ordinary ray at 90° rotation—*i. e.*, when the optic axis is horizontal. The symbol of the extraordinary ray index is ε, and intermediate values are designated ε'. From the first position chosen (the optic axis vertical) these conditions hold for a rotation on *any* horizontal axis. Or, stated differently, if the optic axis is inclined any amount to the axis of the microscope, then the crystal may be rotated on an axis parallel to the optic axis without changing the optical properties.

From this it follows that any uniaxial crystal chosen at random between crossed nicols has two extinction positions (as does a biaxial crystal) and at extinction the optic axis lies inclined in the plane of one of the nicols. (Two exceptions are, that in which the optic axis is vertical and that in which the optic axis is horizontal. Both of these are assumed to be eliminated by the random choice.) If the inclination of the optic axis to the axis of the microscope is increased by rotation on a horizontal axis which lies in the plane of the other nicol then extinction is not disturbed since the optic axis continues to remain in the plane of a nicol. If, however, the crystal is rotated on a horizontal axis which lies in the plane of the same nicol in which the optic axis lies then the crystal departs from extinction since the optic axis is thereby rotated out of the plane of the nicol. This simple test is quickly made on the universal stage to determine the position of the optic axis.

A crystal (uniaxial or biaxial) not in an optic axis position (*i e.*, the optic axis parallel to the axis of the microscope) may transmit two rays. When the vibration directions of these are parallel to the vibration planes of the nicols the crystal is at extinction. By removing the upper nicol, one ray alone is transmitted to the eye—that which is vibrating parallel to the polarizer. A rotation of 90° on the microscope stage causes the other ray alone to be transmitted since its vibration direction is thus made parallel to that of the polarizer. In intermediate positions both rays are transmitted, and *not* a ray of intermediate index, though one ray predominates in intensity when its vibration is closer to that of the polarizer.

If a uniaxial crystal is rotated on a horizontal axis in such a way as to change the refractive index value of the extraordinary ray, this change follows a known course which is used in our determinative procedure. This is discussed in detail in a succeeding section since the principle applies also to biaxial crystals.

Biaxial Crystals have two optic axes. The angle between them differs for different substances, and for pure compounds it is a characteristic value. In isomorphous mixtures the angle may range with the increase or decrease of one component. Uniaxial crystals are essentially a special case of biaxial crystals in which the optic axes coincide. The plane in a biaxial crystal in which the optic axes lie is known as the optic plane and is a plane of optic symmetry of the crystal. There are two other planes of optic symmetry which are perpendicular to the optic plane and to each other. (Fig. 1). These three mutually perpendicular symmetry planes offer probably the simplest key to the practical understanding of biaxial crystals on the universal stage for in them lie most of the transmission and vibration directions of interest. Of fundamental importance is the precept that if the axis of the microscope lies in a plane of symmetry then the vibration directions of both possible transmitted rays also lie in planes of symmetry. One of these vibration directions lies in two planes of symmetry—that is, parallel to the line of intersection of two planes of symmetry (the two in which the transmission direction does not lie). The other vibration direction lies in the same plane of symmetry as the transmission direction. If the axis of the microscope is parallel to a line of intersection of two symmetry planes, then both vibration directions are parallel to similar lines of intersection. By definition the rays chosen as critical are those which vibrate parallel to lines of intersection of these symmetry planes. Obviously when the axis of the microscope lies in a symmetry plane one of the two rays is critical. But only when the axis of the microscope is parallel to a line of intersection of the symmetry planes do both the transmitted rays have critical vibration directions. Following an established custom[2] we shall name the critical vibration directions α, β, and γ. α and γ are the bisectrices, β is the optic normal.

Let us assume that the axis of the microscope is parallel to α which is one of the three possible "oriented positions". The two possible transmitted rays vibrate parallel to β and γ. When these directions

[2] The official committee on nomenclature of the Mineralogical Society of America, in joint session with the British Mineralogical Society committee on nomenclature "approved alpha, beta and gamma as the symbols for both indices of refraction and vibration directions" (Kerr, 1936). The Mineralogical Society of America then voted on the committee's report in 1938. The report was adopted with only one dissenting vote (Kerr, 1939).

parallel the nicols the crystal is at extinction. If the crystal is rotated from one of these extinction positions on a horizontal axis parallel to β, then β remains perpendicular to the axis of the microscope. Since, however, the vibration directions of transmitted rays are perpendicu-
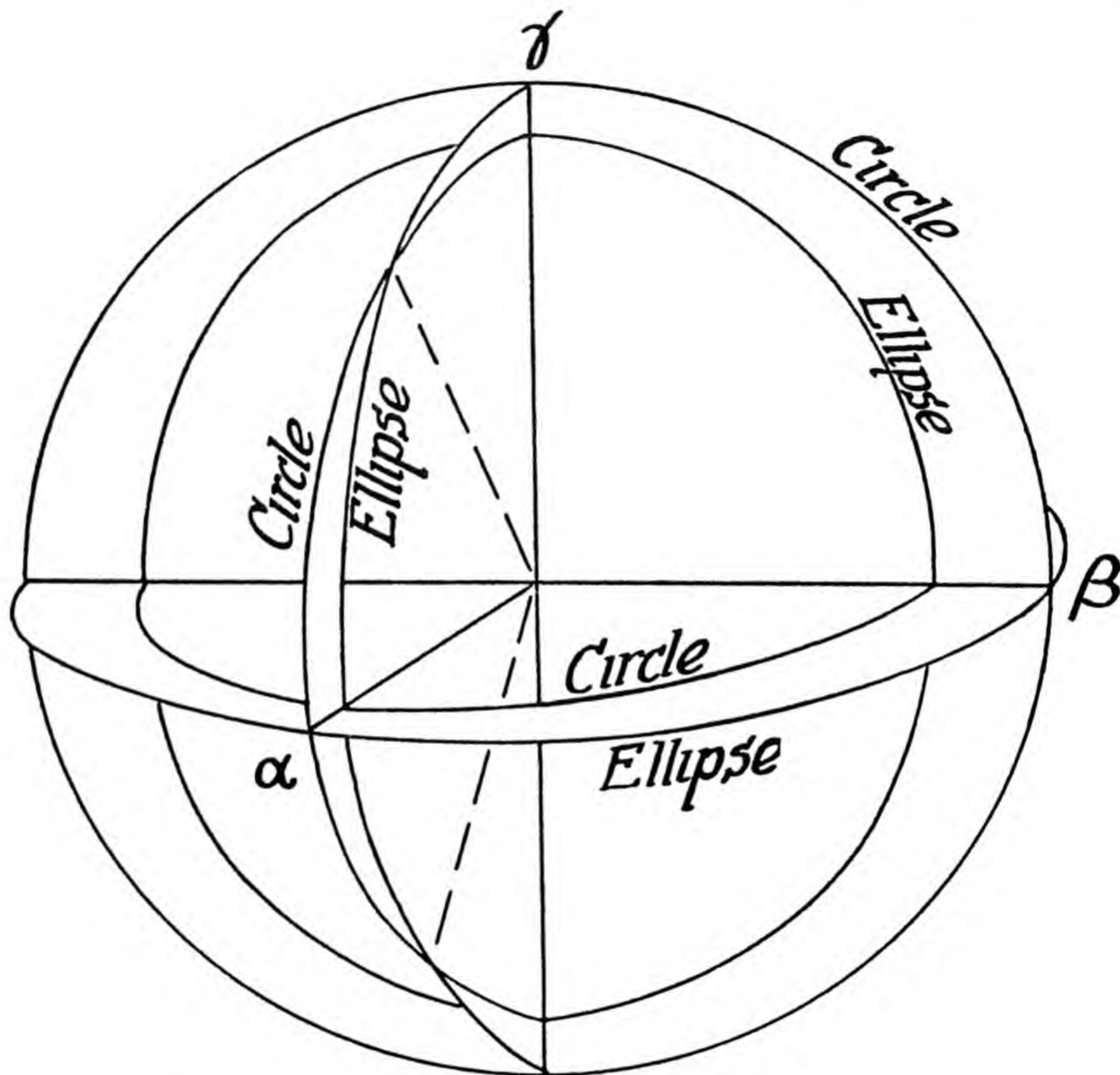
FIGURE 1.—*Optic symmetry planes of biaxial crystals*
With appropriate wave surfaces indicated.

lar (or nearly so) to the axis of the microscope then that vibration direction which was parallel to γ changes with rotation to become parallel to α. But the index of the ray depends upon its vibration direction. Therefore the mean ray β remains unchanged while the slow ray γ changes with the rotation to become the fast ray α on a rotation of 90°. At no time does the vibration direction of either ray leave an optic symmetry plane. At some intermediate position of the rotation, the changing ray equals the mean ray β in refractive index, — this position is that in which the optic axis coincides with the axis of the microscope.

Similarly we may have rotated on the axis γ instead of β. In this case the slow ray γ would remain unchanged, while the mean ray β would change in refractive index from β to α on a rotation of $90°$.

Assume next that the axis of the microscope is parallel to β. The two possible transmitted rays are α and γ, and the crystal shows its maximum birefringence. Again let us rotate on each of two horizontal axes which are parallel to these critical vibration directions. A rotation on an axis parallel to α causes no change in α, but causes γ to change toward β. And a rotation on an axis parallel to γ causes no change in γ, but causes α to change toward β.

Lastly if the axis of the microscope is parallel to γ then the two possible transmitted rays are α and β. A rotation on an axis parallel to α as before causes no change in α, but causes β to change toward γ. And a rotation on an axis parallel to β causes no change in β, but causes α to change toward γ.

Each of these rotations is routine in immersion work and should be thoroughly understood by the student beginning this type of work. These few simple concepts are almost all that are needed in routine crystal orientation and manipulation.

It is apparent that a crystal in an "oriented position" (*i.e.*, a position in which α, β, or γ is parallel to the axis of the microscope) may be rotated on a horizontal axis parallel to either of the other critical vibration directions, and the possible transmitted rays will vibrate in planes of optic symmetry. Furthermore, as the vibration directions change from one critical direction to another as outlined, the changes in refractive index may be calculated as brought out below, by simple graphical means. This becomes an integral part of the determinative procedure.

A rotation of the stage of the microscope does not of course affect the indices of the possible transmitted rays. If the crystal is at extinction between crossed nicols, then on removal of the analyzer only the ray vibrating parallel to the plane of the polarizer is transmitted. *A rotation of an oriented crystal on a horizontal axis which lies in the plane of the polarizer does not change the properties of the transmitted light.* But a rotation on an axis perpendicular to the polarizer does change the refractive index as outlined. This procedure is used extensively in universal stage studies and should be clearly understood; it is especially important in immersion work. At all times the relation of the vibration plane of the polarizer to the axes of rotation of the universal stage is important. Hence it is desirable to place the polarizer so that its vibration plane is always the same—prefer-

ably N-S. The E-W horizontal axes of the universal stage are then perpendicular to the plane of vibration of the polarizer, and the outer E-W axis is most convenient to use.
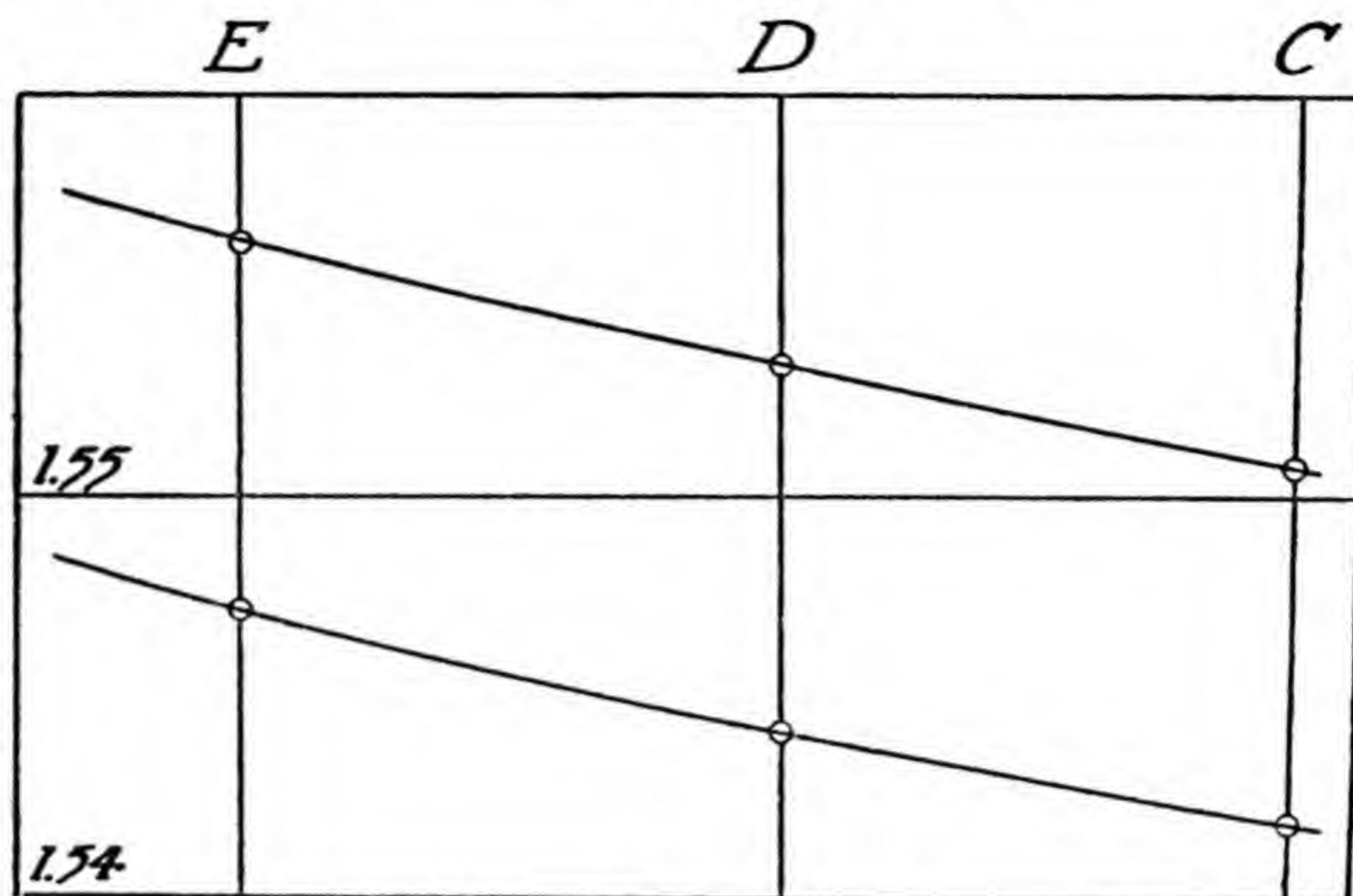
a. The dispersion curves of ε and ω for quartz plotted on a uniform wave-length scale.
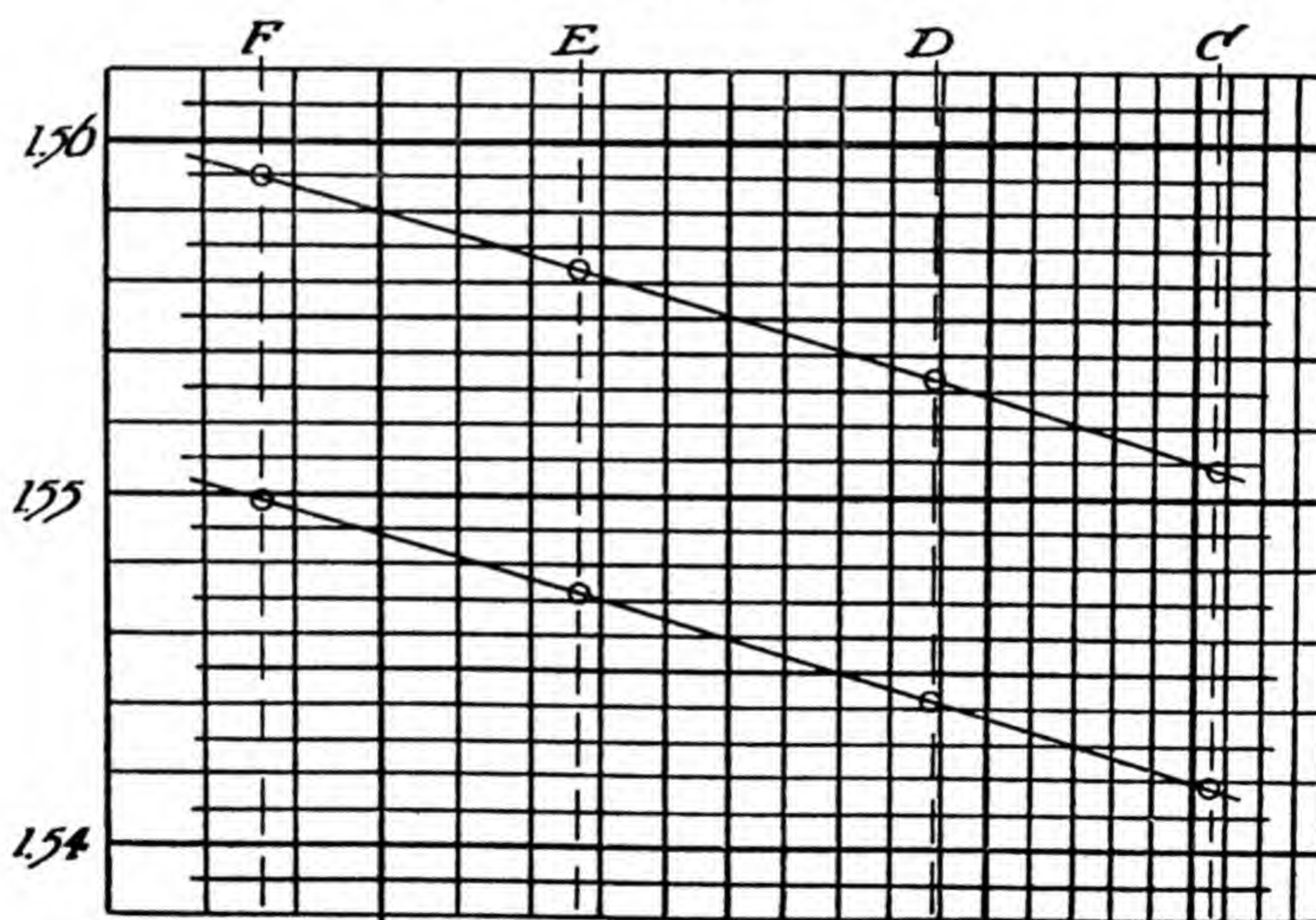
b. The same dispersion curves plotted on a Hartmann dispersion net to convert them to straight lines.

FIGURE 2.—*Dispersion curves*

The wave surface diagram of a biaxial crystal shows for each of the three optic symmetry planes a circle and an ellipse. The explanation is to be found of course in the principles we have discussed, or, vice versa, with the wave surface diagrams in mind the changes in refractive index on rotation of a crystal on the microscope stage

may be forecast. These are the principles mainly needed to orient a crystal.

If the axis of the microscope does not lie in a symmetry plane the vibration directions of the transmitted rays cannot lie in symmetry
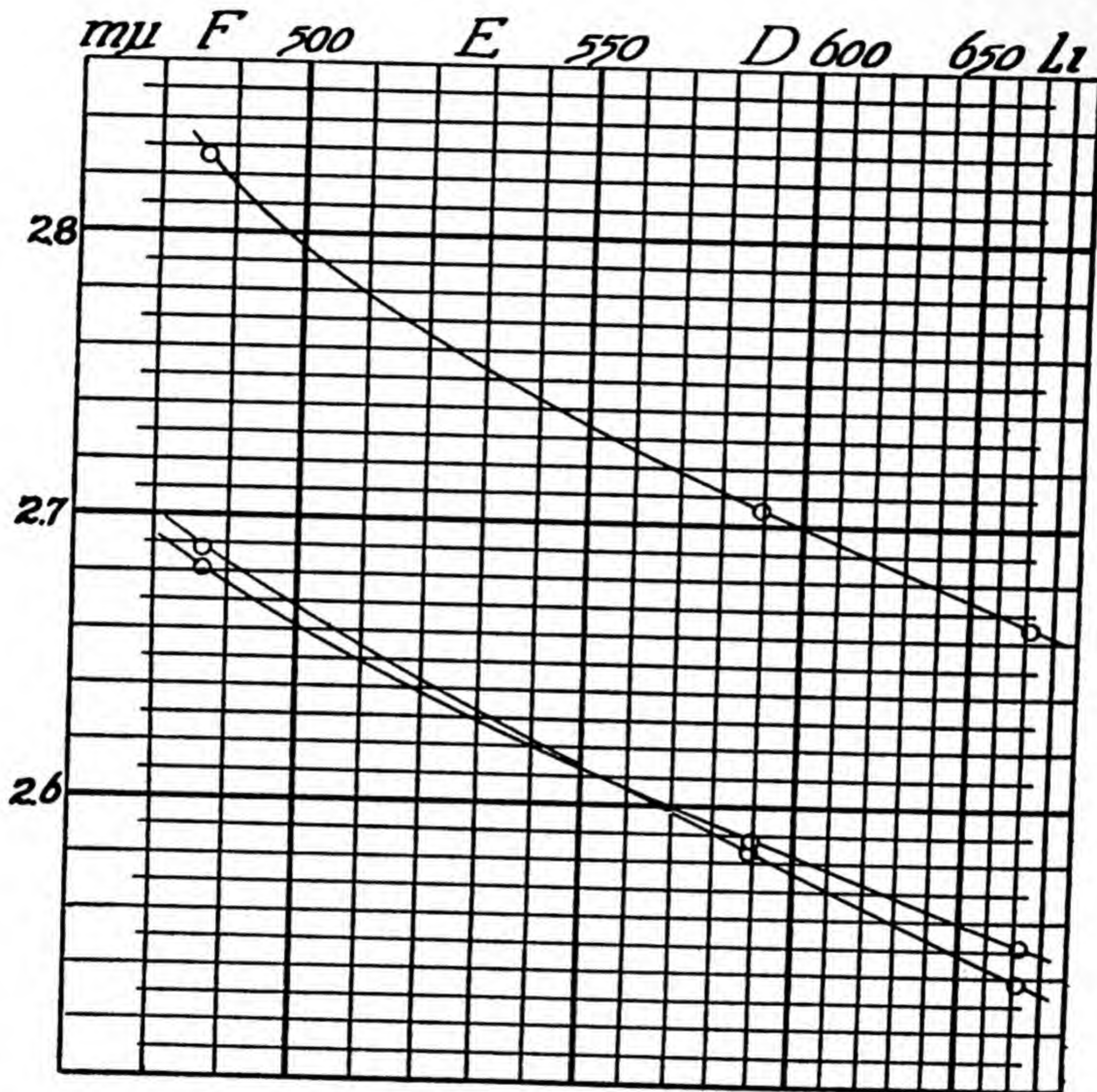
FIGURE 8.—*Dispersion curves of brookite*

Showing two of the curves actually intersecting thereby causing the spectacular crossed dispersion for which brookite is so well known. Note that the curves are not straight lines despite the Hartmann net— a feature of higher-index crystals.

planes. To find, theoretically, the vibration directions find the traces on the plane of the microscope stage, of two planes, each of which includes one optic axis and the axis of the microscope, then bisect the angles formed by these traces, and the bisectors are the vibration directions. The understanding of the procedure of Berek to be described later is dependent solely on this concept which is according to the Biot-Fresnel law.

The refractive indices of crystals are different for different wave lengths of light as is true of transparent substances in general. This is spoken of quantitatively as dispersion and is expressed in most

crystallographic literature as N_F-N_C, the index difference for readings made with light of wave lengths 486mμ and 656mμ. Dispersion of solid substances is in general less than that of liquids, it is usually greater for substances of high index than for those of low index, and
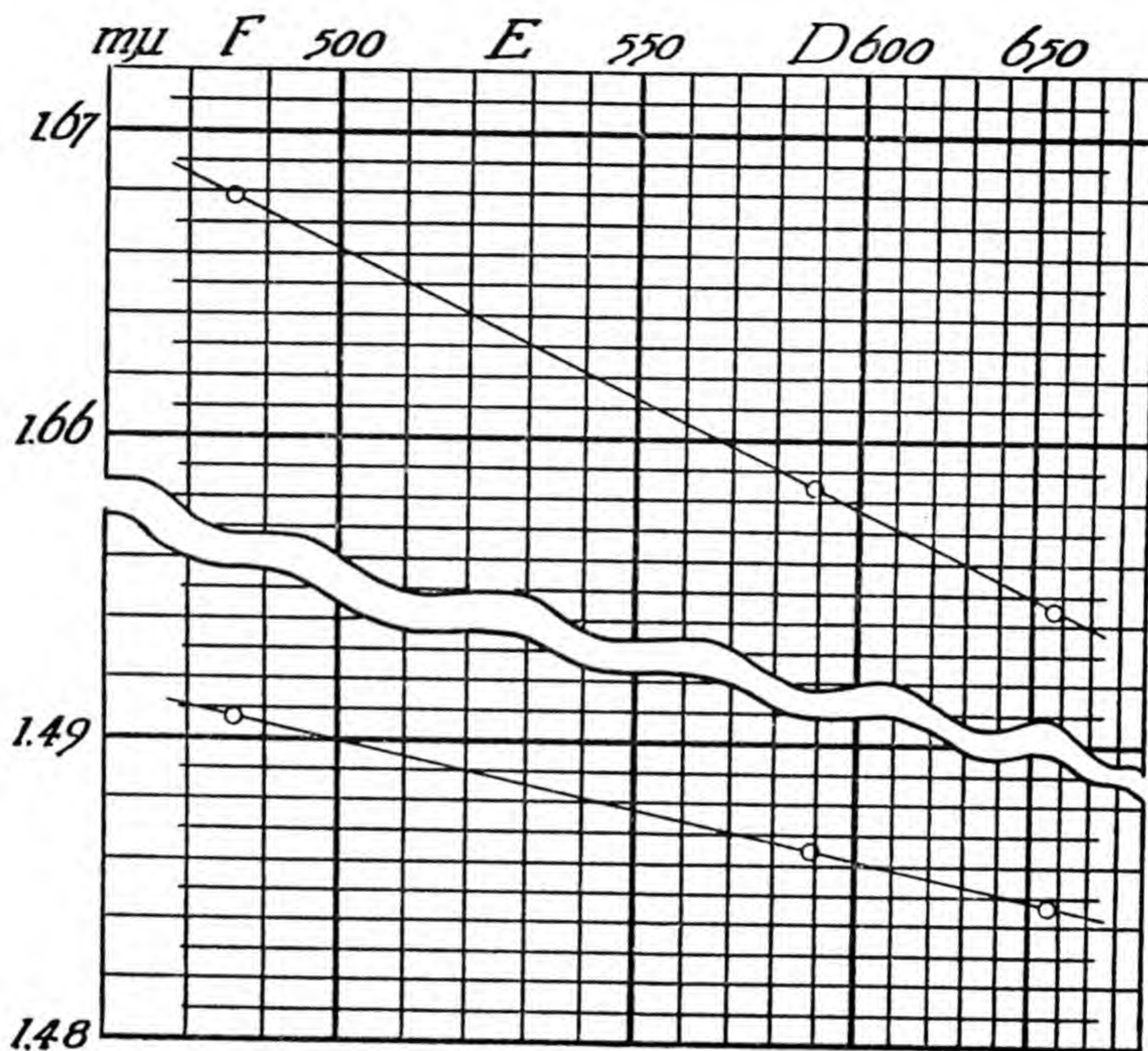
FIGURE 4.—*Dispersion curves of calcite*
Note that the two curves are not parallel.

is in general greater in crystals containing certain elements such as iron and titanium. The plot of the refractive indices of a given substance for different wave lengths on a uniform wave-length scale is a curve (Fig. 2a). On Hartmann's dispersion net (Tsuboi, 1930) in which the wave-length scale is not uniform the result is a straight line for most substances of index below 1.65 and for many above 1.65 (Fig. 2b). If part of the curve is known, the remainder may usually be obtained by extrapolation, especially easily by the use of Hartmann's net but not necessarily in the higher index range. The curves of different substances *may* coincide for only part of their extent but this possibility is not a serious hazard between the F and C lines, particularly below N=1.65. Although the dispersion curves of crystals for the various rays are not exactly parallel, if two points on one curve are known, and one on each of the others

of a biaxial crystal of index below 1.65, then **parallel lines drawn** through the single points give a fair approximation—commonly about ±.001 between F and C. There are numerous exceptions, notably for crystals of higher indices, especially well illustrated by brookite in which two of the curves actually cross (Fig. 3). In crystals of high birefringence the dispersion curves are usually not parallel (Fig. 4).

Chapter 2
General Considerations in Universal Stage Work

THE universal stage is designed to make possible the orientation of any crystal so that one of its critical vibration directions is parallel to the axis of the microscope and the others are perpendicular to it. For this purpose there are five rotational axes whose purposes are (1) to facilitate the recognition of critical crystallographic directions, and (2) to adjust these directions with respect
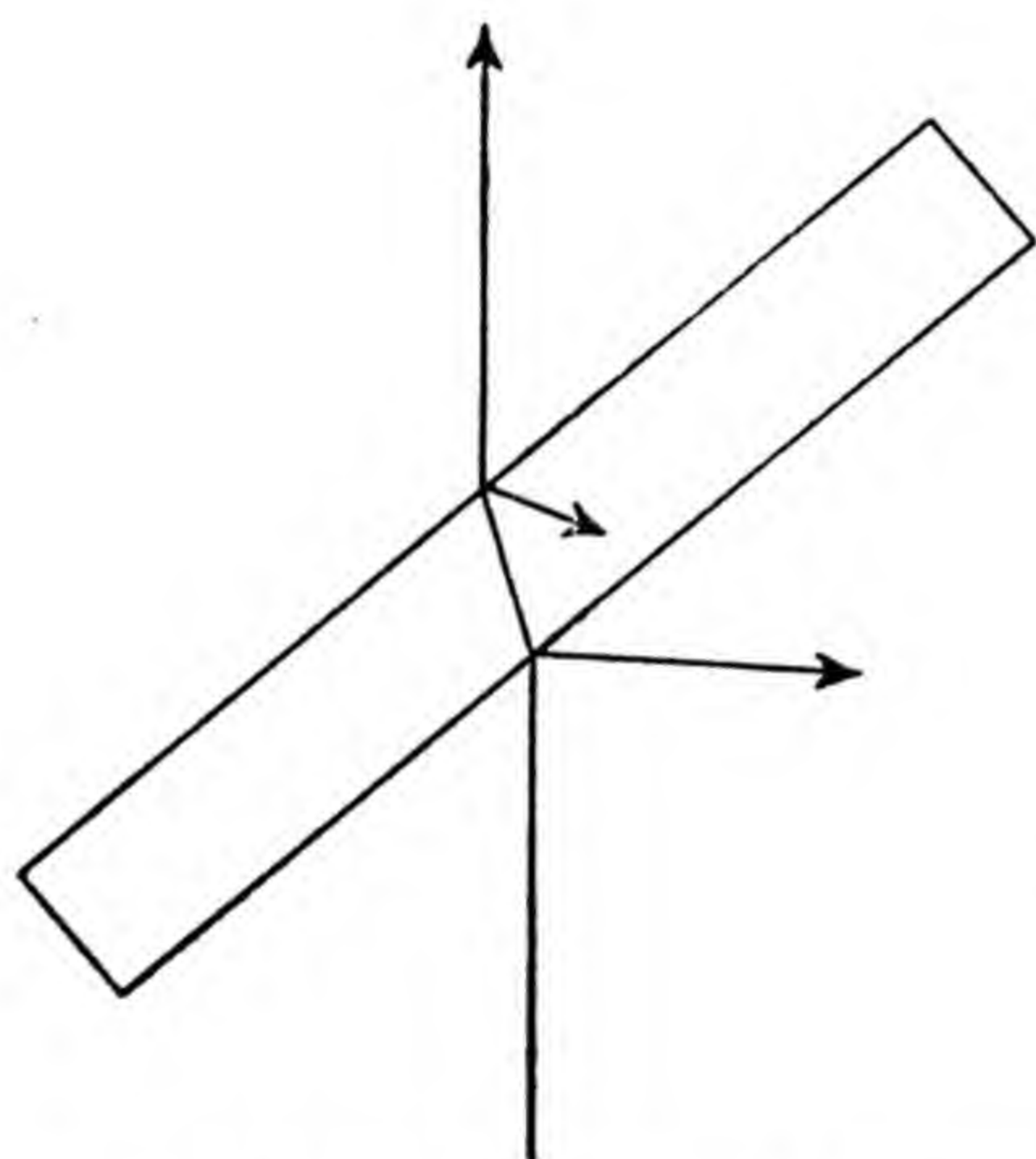
FIGURE 5.—*Light transmission and reflection in an inclined plate*
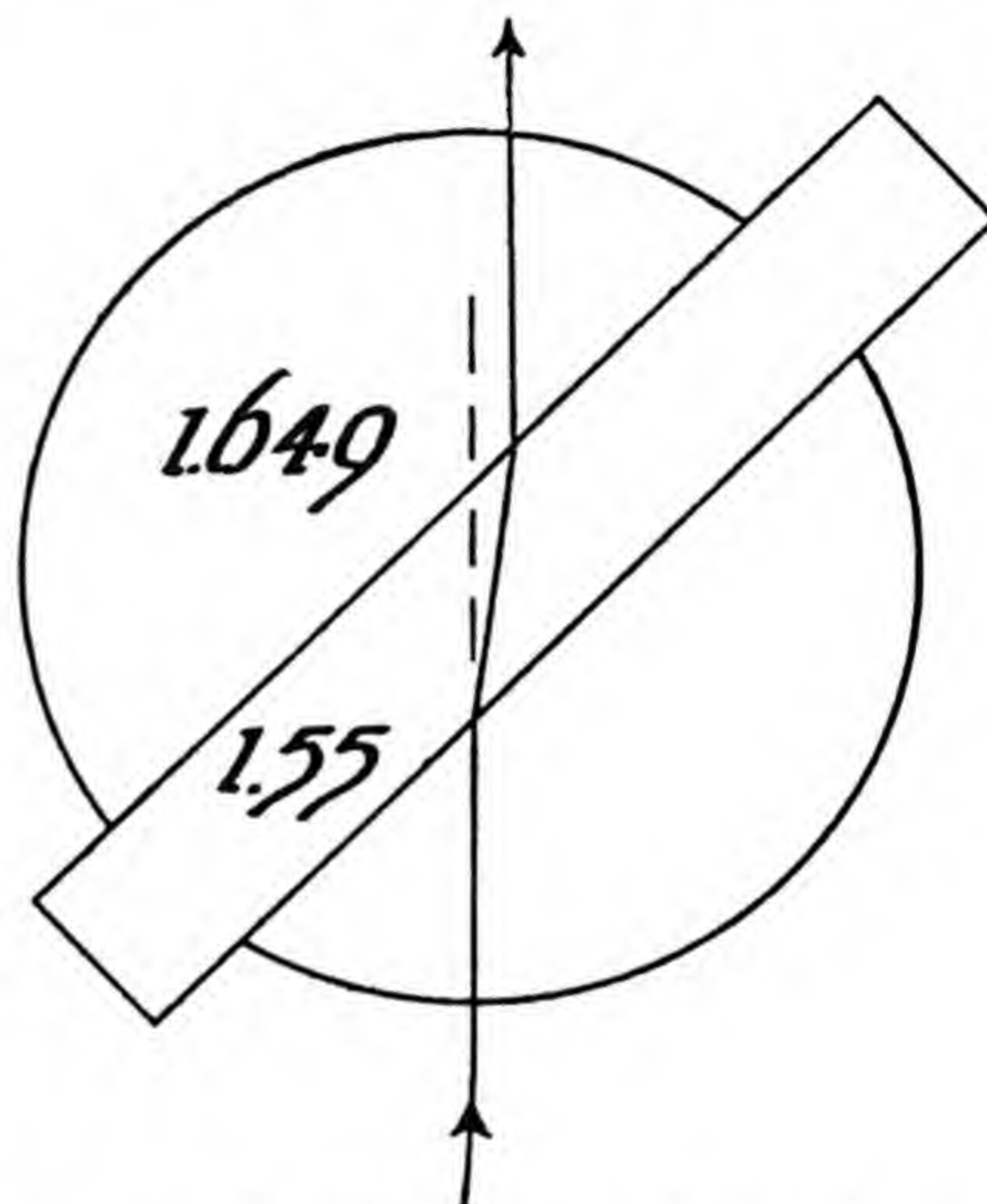
FIGURE 6.—*Light transmission in an inclined plate on the universal stage*

to the microscope. The optical constants of the crystal may then be determined with the confidence that they are truly critical. Direct readings may be made on such values as the optic angle by rotating measurable amounts from known positions.

The crystal fragment being studied, whether in thin section or in an immersion medium, lies in a tabular layer of material. If in thin section the crystal itself is cut to a tabular shape, if in an immersion medium the crystal and medium are made to agree essentially in index. In either case from the point of view of rotation we may consider the optical effect of inclined incidence of light on a tabular transparent body. Incident light on such a plate at an angle in air enters the body in part, though to some extent it is reflected, regardless of the angle of incidence, since the refractive

index of the plate is higher than that of the medium (air) from which the light strikes. On reaching the remote side of the plate the rays are passing from a medium of high index to one of low index (air), and here again partial reflection takes place (Fig. 5).
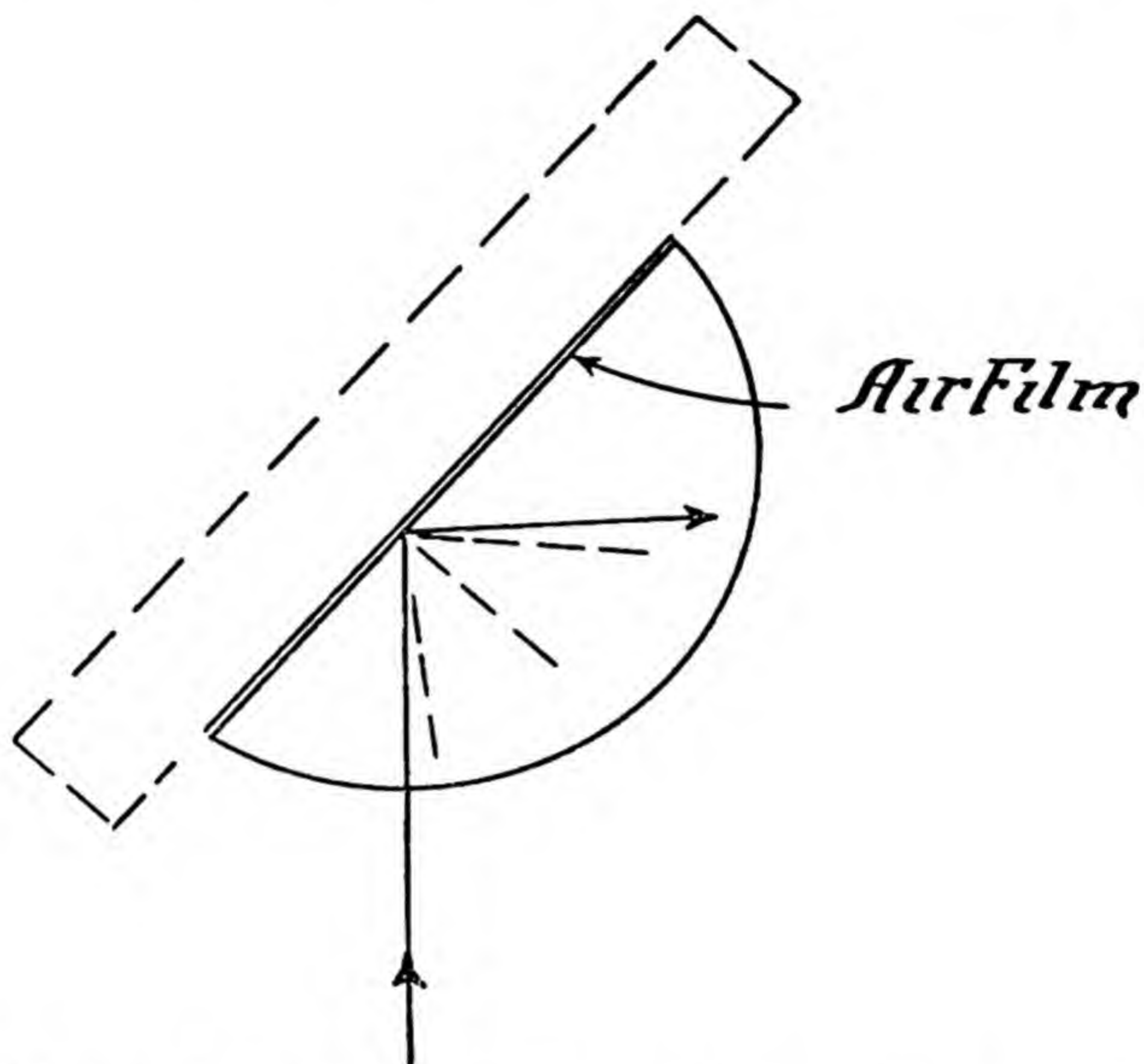
FIGURE 7.—*Air film between glass surfaces causing reflection beyond the critical angle*
This is overcome by using cedar oil or some other liquid at the contacts.

Further, although the angle of incidence is large, the angle of refraction within the crystal usually is not, and the purpose of rotation is to make this angle large. To avoid these difficulties two hemispherical bodies of glass are placed about the mount, one above and one below, so cut that the crystal is at the center of a sphere (Pl. 2, figs. 2, 6). Incident light is then normal to the surface of the glass for any inclination of the mount. By using hemispheres of index approximating those of the crystal, the change in the light path is reduced to a minimum when the rays leave the glass and enter the crystal. Accordingly reflection is largely eliminated (Fig. 6).

The hemispheres are applied with liquid contacts (cedar oil or glycerine) to eliminate air. Otherwise there would be total reflection at the plane surface of the lower glass hemisphere when the inclination of the mount exceeds the critical angle of the glass (Fig. 7).

DESCRIPTION AND ADJUSTMENT OF THE UNIVERSAL STAGE

The universal stage is diagrammatically represented in Figure 8 and photographically in Plate 1 and Figure 2 of Plate 3. It consists first of an inner plate on which the mount is placed and which
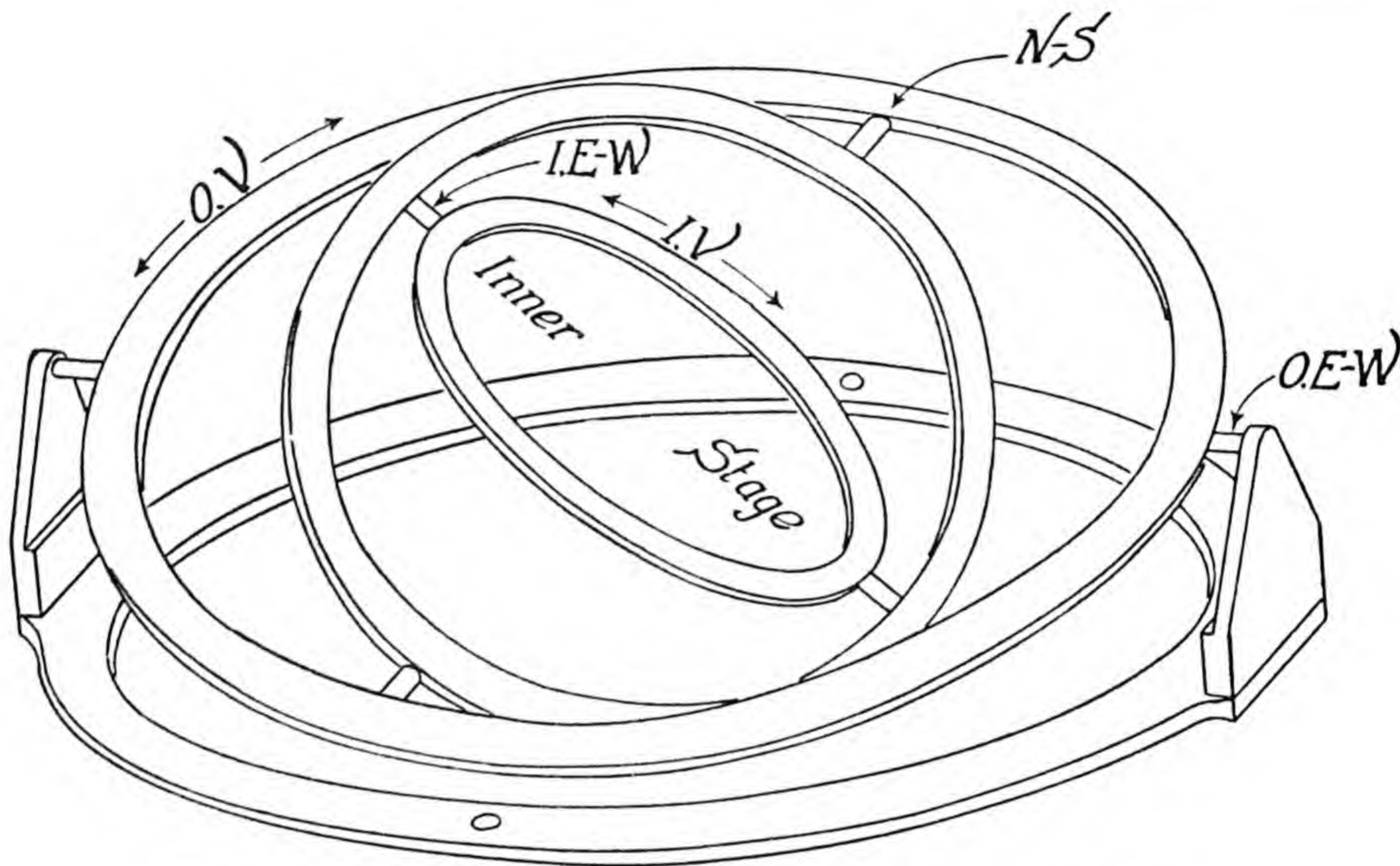
FIGURE 8.—*Diagrammatic view of the five-axis universal stage*

may be rotated on any or all of five different axes, each having its own purpose. First it may be rotated on an axis which is perpendicular to the plate, referred to here as the inner vertical axis.[3] Its rotations are measured by a graduated circle. Next, this plate and its

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[3] It would be desirable to have universal agreement in the naming of the axes. In Europe where the stage has been used most there is no agreement whatever. Berek's numbering of the axes is simple to remember but it has no self-evident meaning to recommend it. Further, it was developed for the four-axis stage to which it is adapted. To apply it to the five-axis stage as Doeglas suggests would require either renumbering the axes, leading to tragic confusion, or numbering the inner east-west axis "six," which is entirely illogical, since it belongs between one and two. After careful thought it was decided to cater to the English-speaking petrographer by using an English terminology rather than to adopt, without reason, one of the foreign systems among which there is no choice. The names used here are the obvious ones which any beginner would give the axes, and they can be used conversationally without effort by one who has just examined a stage for the first time. The abbreviated symbols, being the initial letters of the names, are also obvious. The following table gives the correlations of the different nomenclatures. Reference may be had to Figure 8.

	Present paper	Reinhard	Berek	Duparc-Reinhard	Fedorow-Nikitin
Inner vertical axis (I. V.)		N	A_1	N	N
Inner east-west axis (I. E-W)		—	—	—	—
North-south axis (N-S)		H	A_2	H	H
Outer vertical axis (O. V.)		A	A_3	M	M
Outer east-west axis (O. E-W)		K	A_4	J	J
Microscope axis (M)		M	A_5	—	—

graduated circle may be rotated on an axis which is normally horizontal and extends in an east-west direction, referred to as the inner east-west axis. Third, this axis is suspended on an ungraduated ring which may be rotated on another horizontal axis extending in a north-south direction—the north-south axis. On this ring at its north and south sides are two folding arcs (known as Wright arcs) which when raised serve to measure rotations on the inner east-west axis. These rotations are recorded in degrees north or south according to the inclination of the perpendicular to the inner stage. The north-south axis is suspended on another ring which may be rotated on an axis normal to the ring, referred to as the outer vertical axis. This ring is graduated in degrees. Rotations on the outer vertical axis are read on a vernier at the west side. Also, at this side and opposite to it are two more Wright arcs which when raised serve to measure rotations on the north-south axis. They are recorded in degrees east or west as they affect the inclination of the perpendicular to the inner stage. Lastly, the outer ring may be inclined north or south on an east-west axis, controlled by a knurled and graduated drum at the east side. Readings on this drum are read on a vernier. This axis is referred to as the outer east-west axis. Rotations on any of these axes in the order named affect the attitude of each of the axes above them in the sequence. The instrument is mounted on the stage of the microscope and may of course be rotated on this as a sixth axis. The elevation of the inner stage may be adjusted to bring the mount to center in a vertical direction. Ideally all six axes intersect at a point which is the center of all rotations. Actually, a considerable tolerance is to be allowed in a moderately priced instrument. All axes are provided with clamps to hold them in any desired position. Since an instrument of this sort is delicately built, special care must be taken not to force any movable parts, lest they are clamped. *The finger tips alone are needed.*

Recent modifications have made it possible to make both thin-section and immersion studies on the universal stage. A thin section mount is made as follows: Place the glass plate in position on the inner stage. On this place a drop of glycerine or cedar oil and then the thin section. Direct the length of the thin section across the direction joining the screw holes for the upper hemisphere. On the thin section place another drop of oil and then set the upper hemisphere in place and with the thumb screws gently tighten it. The length of the thin section is then perpendicular to the length of the hemisphere mount and in this position permits greater lateral movement of the section for centering a chosen crystal. Place a

drop of oil on the upper surface of the lower hemisphere and insert it from below.

In an alternate model Bausch & Lomb stage, designed by L. V. Foster of that company, the entire inner stage forms a removable unit. The thin section and hemispheres are set in place, held by spring clamps instead of thumb screws, and the whole is then set and clamped into the universal stage. Although mounts are changed without removing the universal stage from the microscope, this newest feature makes such changing especially convenient (Pl. 2, fig. 7).

The universal stage must be centered accurately on the microscope stage so that the microscope axis may have a common intersection point with the universal stage axes. A central ring of the microscope stage is removed before the universal stage is attached. This permits greater rotations of the outer east-west axis without excessively raising the height of the accessory. The universal stage is fastened to the microscope stage by two thumb screws provided for the purpose. To center the universal stage first rotate the microscope stage to be sure that the objective is centered. Then clamp the microscope stage, rotate on the outer vertical axis, and note the center of rotation. Unclamp the thumb screws holding the universal stage and bring this center to the cross hairs. Now clamp the thumb screws *tightly*. A rotation on the inner vertical axis should also be centered reasonably well. If it is badly off center the instrument is at fault and cannot be corrected by adjustment.

The elevation of the mount may be adjusted next. Rotate on the outer east-west axis and note whether the mount swings in an arc downward or upward. If upward then the mount is too low, if downward, it is too high, since the microscope reverses the image. The observation may also be made by noting whether a particle moves north or south on a rotation to the north or south. If it moves in the same direction as the rotation the amount is too low, if in the opposite direction, too high. This may be checked by focusing sharply on an object when the inner stage is horizontal, then inclining steeply and refocusing, noting whether the focus is now above or below its former position. Adjustment is made by turning on its threads the collar which supports the inner stage plate. On some models the thumb screws of the upper hemisphere mount must be adjusted to permit the vertical adjustment. When the elevation is correct an object at the cross hairs remains in place on rotation on the outer east-west axis. Next rotate on the north-south and inner east-west axes. If the stage is ideally built the object at the cross hairs will remain in position as it was made to do for a rotation on the outer

east-west axis. However, this condition must not be expected. (Tolerance = .003 inches.) Nor should the departure from center be great, as it cannot be corrected by adjustment of the instrument. Some stages are not equipped for vertical adjustment of the mount. An abnormally thick or thin slide may then be troublesome. If too thin it may be raised by placing one or more cover glasses beneath it, each with liquid contact, of course.

The horizontal axes must now be aligned with respect to the nicols. If the cross hairs have not been checked with reference to the nicols this should first be done by noting extinction on a suitably elongate crystal having parallel extinction.[4] This should be done on any new microscope regardless of universal stage work. We shall assume then that the cross hairs are in the planes of the nicols. Using the lowest-power objective available, rack up the tube of the microscope to focus on the upper surface of the upper hemisphere. Then rotate

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[4] Mr. Zieler of E. Leitz Co. recommends using bichloride of mercury prepared from a concentrated solution evaporated on a heated slide.

EXPLANATION OF PLATE 2

FIGURE

1. Water cell for temperature control on the universal stage. Lower side shows lower hemisphere which may be removed for cleaning. (Figures 1, 2, and 3 are photographs by the Bausch & Lomb Optical Co.)

2. Upper and lower hemispheres for the universal stage. This type of lower hemisphere is used for thin section mounts only. This type of upper hemisphere may be used for immersion mounts or for thin sections; it allows the maximum movement of the slide.

3. Upper side of the water cell of Figure 1. Immersion mounts are made on this surface. The glass plate may be removed from the cell for cleaning.

4. L. V. Foster's modified water cell. Special upper hemisphere shown in Figure 6 is used with this cell. This cell offers the advantage that the mount may be removed from the stage without disturbing a studied grain. It also makes the preparation of a mount especially convenient.

5. Special universal stage objective, UM3 by E. Leitz Co. This objective is used with standard size hemispheres.

6. Upper hemisphere (Foster's design) to be used with the cell shown in Figure 4.

7. Bausch & Lomb's special apochromatic objective and the hemisphere used with it, showing a complete mount according to Foster's design. This objective, 20×, together with a 30× compensating ocular, yields a magnification of 600 on the universal stage.

8. Bausch & Lomb's special 20× achromatic objective and hemisphere which with a 15× hyperplane (or periplane) ocular yields a magnification of 300.

9. Gauss mirror accessory and cross-hair accessory for checking the settings of the horizontal axes of the universal stage.

PLATE 2

SOME ACCESSORIES TO THE UNIVERSAL STAGE
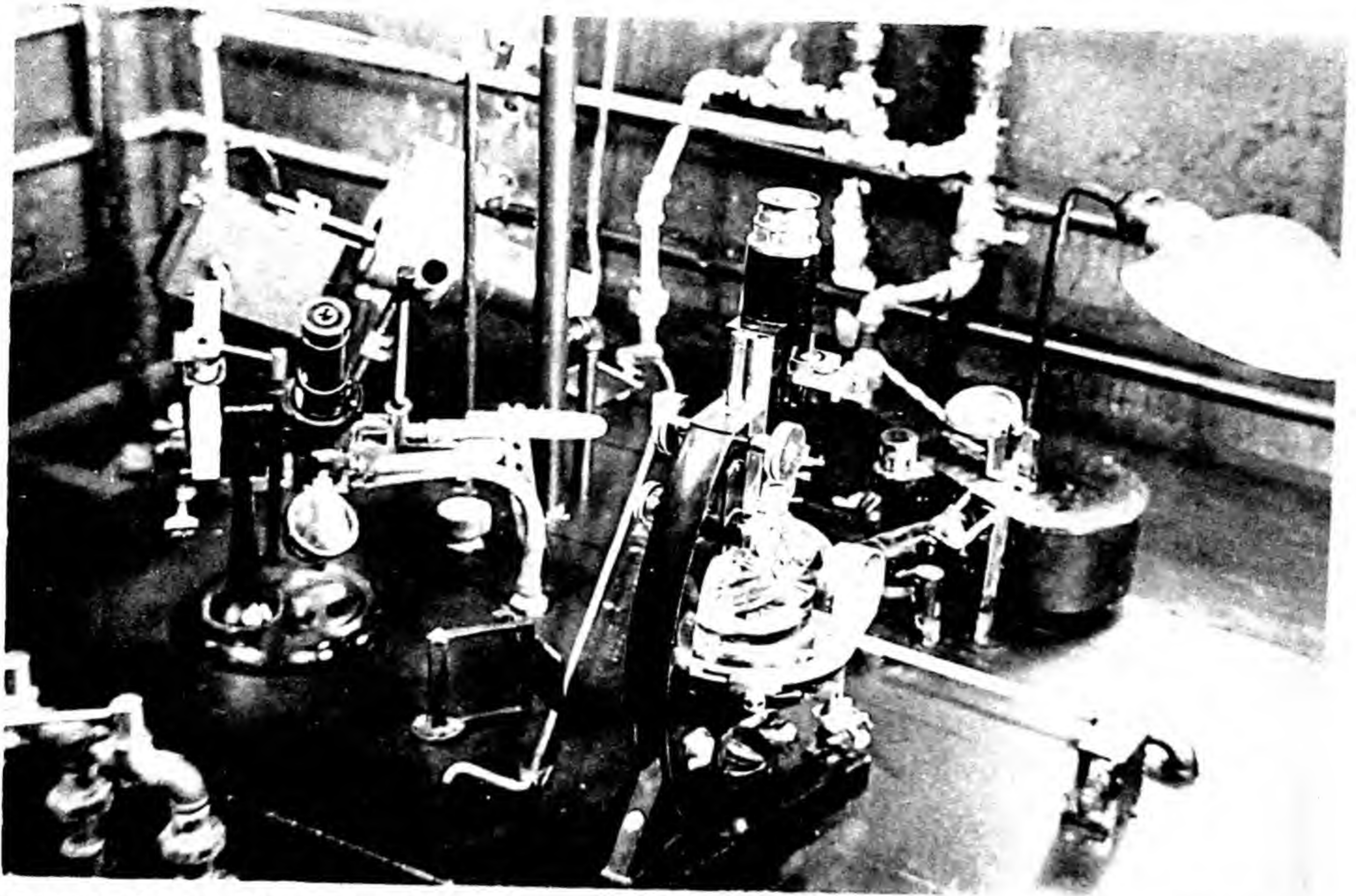
FIGURE 1. ONE OF THREE DOUBLE-VARIATION UNITS IN MINERAL LABORATORY AT UNIVERSITY OF WISCONSIN
(Photograph by D. S. Turner.)
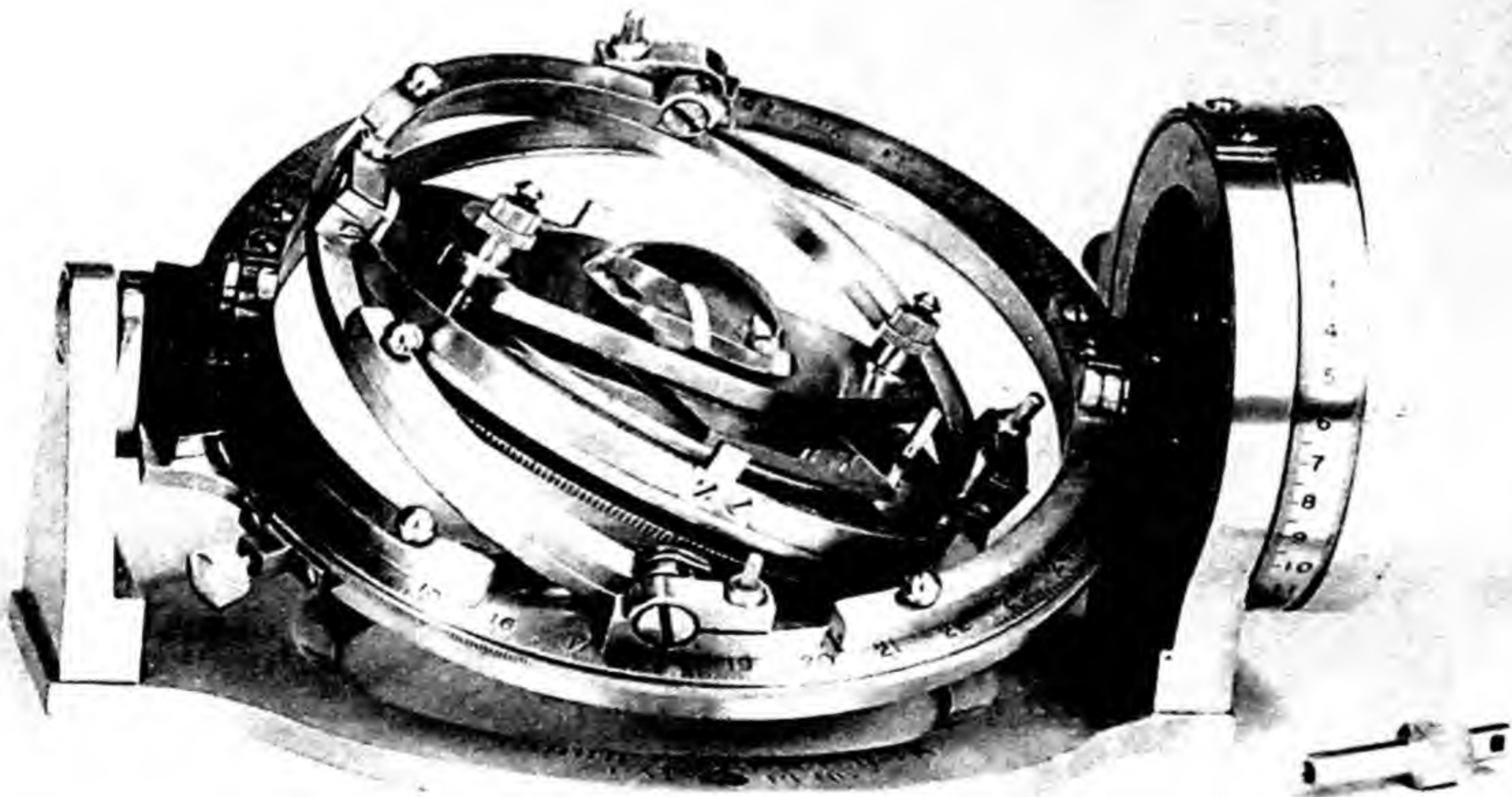
FIGURE 2. BAUSCH & LOMB FIVE-AXIS UNIVERSAL STAGE
(Photograph by the manufacturer.)

UNIVERSAL STAGE AND ITS USE IN DOUBLE VARIATION

on the outer east-west axis and notice if the dust particles follow the cross hair. Rotate the microscope stage enough to make them do so and clamp the microscope stage in this position. Record the vernier reading for it is the zero position of the microscope stage for the setting. This must be done each time the universal stage is mounted on the microscope stage. Next, rotate similarly on the north-south axis and adjust the outer vertical axis to make dust particles follow the other cross hair. This reading on the outer vertical axis is also recorded, as it is the zero reading for the axis and is fixed for the instrument. The inner east-west axis cannot be adjusted but it is less important that it should be though ultimately a universal stage provided with this adjustment may be manufactured. The universal stage is now ready for operation. With practice these steps require little time indeed. However, it is convenient to leave the universal stage on a microscope if feasible.

A special accessory is provided by E. Leitz Co. for checking the zero readings of the horizontal axes. It is a gauss mirror in a mount which replaces the analyzer (Pl. 2, fig. 9). It includes a cross hair which slips over the front lens of the objective. It is illuminated with a lamp at the side of the microscope. Set the inner east-west axis at its zero position, then adjusting the north-south and outer east-west axes and focusing on the inner stage plate make the reflected cross hairs coincide with the real image. The north-south and outer east-west axes should now be at their zero readings.

Correct illumination of the stage is most important. A strong light source is desirable, a shielded arc lamp preferred. Better results are obtained by working in a dark room where the eyes are protected from broad daylight. The arc lamp is directed onto the microscope mirror squarely and centered by inserting the Bertrand lens and adjusting the mirror. The diaphragm below the polarizer may profitably be cut down. This diaphragm may be obtained as a clamp-on accessory if the microscope is not provided with it. Another desirable accessory is an ocular which carries a diaphragm, thereby cutting down the size of field and directing the attention more completely onto the centered crystal. For accurate work an objective with a diaphragm aids in sharpening extinction by confining observations to more nearly parallel light. It is well to check the centering of the illumination occasionally during the progress of work as the light beam is easily thrown off center. *Centered illumination is essential to accuracy.*

A powder immersion mount may be made with a slide and cover glass as though it were a thin section. Preferably, however, it is

made for study under controlled temperature as follows. In place
of the central glass disc, use a water cell (Pl. 2, figs. 1, 3, 4) which
consists of a metal mount including a lower hemisphere on one side
and a glass plate on the other. Two nipples for hose connections
permit water circulation through the cell. Light-weight, very flexible
rubber tubing should be used and is best directed through the open-
ing in the microscope stage to the supply leads. On the upper surface
of the cell place a drop of the chosen immersion liquid and cover
it with a round cover glass. On this place another drop or two of
immersion liquid and introduce the material to be studied. Avoid
using a large amount of material—a sufficient amount is two or three
grains. A mass of grains will move on inclination of the stage and
conceal the grain being studied. Cover with another cover glass
and add another drop of liquid. Place the upper hemisphere and
gently tighten the thumb screws. The mount is thus placed be-
tween two cover glasses which protect the optical surfaces of the
cell and hemisphere. Under no condition is the mount to be made
directly on the cell without a cover glass, nor is the upper hemisphere
to be placed directly on the uncovered mount. Examine the field
and if a suitable grain is not near the cross hairs incline the stage.
The grain selected, when the upper hemisphere is slightly loosened,
will fall apparently uphill because of reversal of the image by the
microscope. Gentle movement of the upper hemisphere aids this
centering of a grain. When the grain is suitably close to the cross
hairs, bring the inner stage back to horizontal and *gently* tighten
the upper hemisphere. Vigorous tightening will either strain or
shatter the grain. In fact the grain if too large may be easily broken
by increasing the tension on the spring clips or thumb screws. The
two cover glasses help to protect the optical surfaces of the upper
hemisphere and the water cell. The mount should next be inclined
steeply in various directions to be sure that the grain chosen is
held in place. The hose leads should be loose to avoid possible slight
movement of the water cell which may disturb the grain. *Avoid, in
subsequent rotations, placing the fingers on the upper hemisphere
thumb screws or mount* as this too may disturb the grain. Four
posts on the inner stage are for convenience in rotating the inner
stage on either of its axes. In studying thin sections two or all of
these posts may be removed to permit greater movement of the
slide laterally. Beginners frequently experience difficulty in retain-
ing grains in place, but this difficulty is almost invariably due to
insensitive fingers and disappears when the manipulation as outlined

is mastered. If the mount consists of extremely small grains it is well to use very small cover glasses (fragments are satisfactory).

Dimler and Stahmann (1940), who recently made a study of some delicate organic crystals in the mineral laboratory at Wisconsin, de-
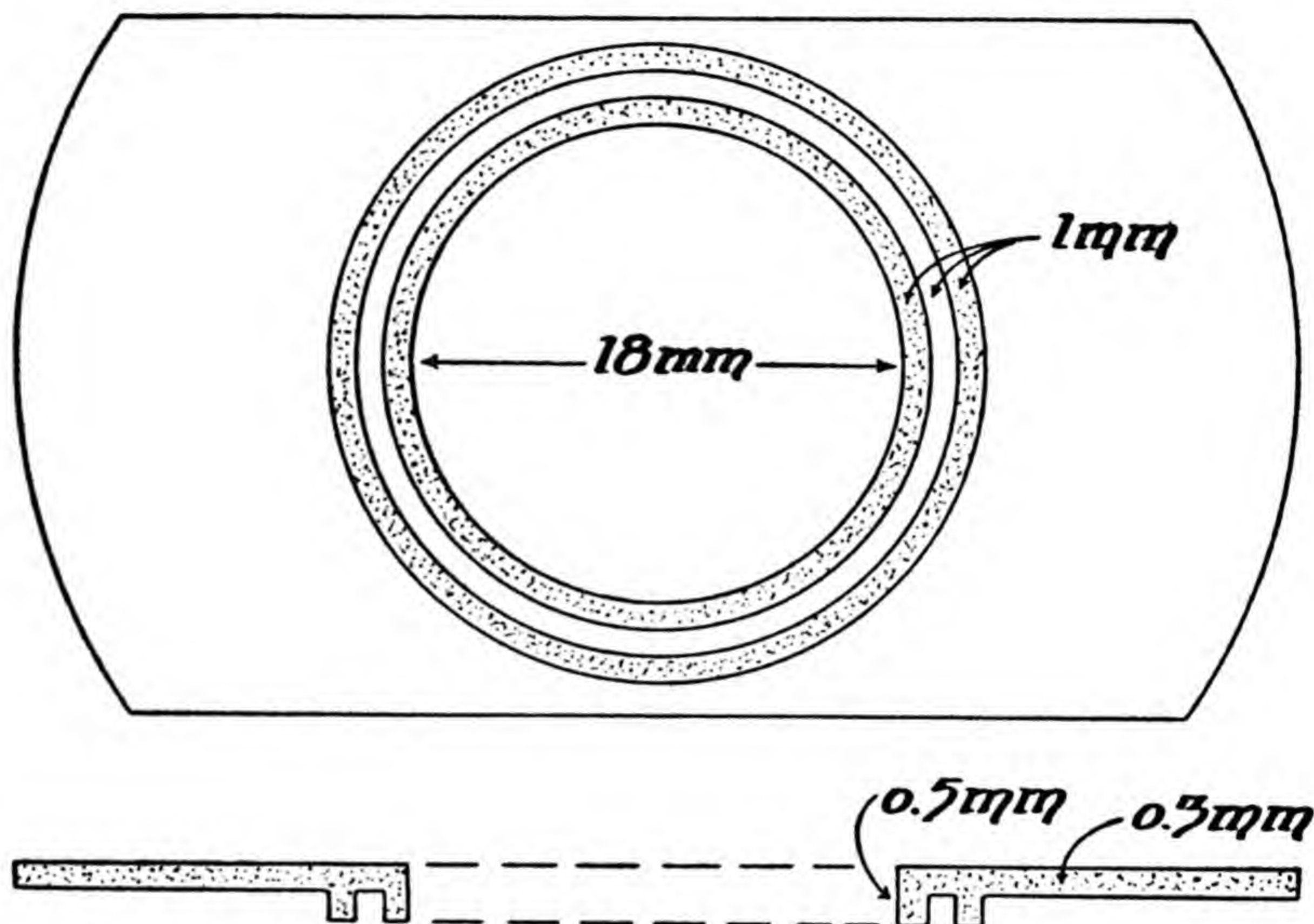
FIGURE 9.—*Metal slide for a grain mount on the universal stage*
This facilitates centering grains and also protects delicate grains. (After Dimler & Stahmann.)

veloped and reported a metal slide for making a mount. It consists of a metal strip (Fig. 9) the approximate size of a standard slide. In this is an opening the diameter of a round cover glass of chosen size. The thickness at the center is equivalent to three cover glasses, and elsewhere is less—leaving thereby a collar around the opening. The collar helps prevent the spread of liquid. The mount is made between cover glasses in the opening. The upper hemisphere rests on the metal collar rather than on the cover glasses, thereby avoiding pressure on the grains. The slide permits moving the mount about as a unit, avoiding disturbance of grain orientation. The weight of the upper cover glass seems to be adequate to prevent the grains from moving on inclination. The thickness of the metal collar must just exceed the thickness of two cover glasses and the mount—this is equal to about three cover glasses.

Strain in the various lenses is more common than is generally realized. It results mainly from pressure of the metal mounts on

the glass or it may develop in a large lens not subjected to outside stress. Such strain is expressed as double refraction of the glass and therefore leads to inaccurate orientations since it modifies extinction. For universal stage work, such defective lenses should be discarded. To detect strain, examine the lens between two sheets of crossed polaroid or insert the Berek compensator and note the effect of the lenses on the resulting interference figure. If one lens is strained, the proper one may be identified by removing or inserting lenses one at a time and noting when the disturbance appears. It is well, too, to rotate the lenses on the axis of the microscope. Hemispheres are especially sensitive to the development of strain. They are rolled loosely in their metal mounts when this can be done, but even this does not always eliminate strain. In water cells this problem is most serious since tight clamping of the glass parts is necessary. In addition to this the strain on the glass is varied by expansion and contraction of the metal with changes in temperature. Periodically the original metal-sealed water cells had to be returned to the factory to have strain removed.

A new design of water cell has just been completed by Bausch & Lomb, which permits removing the glass parts from their metal mounts. They are replaced with rubber gaskets and a wrench provided with the cell. Such a procedure makes cleaning possible and also removes strain.

Foster's alternate inner stage assembly also offers an advantage on an immersion mount. Using a water cell with posts and spring clips (Pl. 2, fig. 4) and the corresponding upper hemisphere (Pl. 2, fig. 6) the complete mount is made in the hand and then fitted to the stage by dropping in place.

The amount of correction for difference in index between crystal and hemisphere depends upon the difference in index. To keep this down to a small figure more than one set of hemispheres is available. As standard equipment the instrument is provided with hemispheres $N_D=1.516$ and $N_D=1.649$. The set of hemispheres is chosen which is closer to the index of the crystal. Also available is a set of hemispheres of index $N_D=1.559$ designed primarily for use in the study of plagioclase feldspars. Water cells may be obtained for these same index values and are selected on the same basis. Avoid laying any of these lenses down in such a way that their surfaces come in direct contact with a table top or such, as the ever-present dust produces scratches.

Standard high magnification in the petrographic sense is now pos-

sible on the universal stage. In routine work the 40 mm, 32 mm, or #1 or #2 objectives are used. These with a 10× ocular give magnifications as high as 60×. Higher magnifications are obtained as follows: Leitz manufactures a special objective of long-working distance, sufficient to accommodate the standard hemispheres and having a magnification of 20×. Such an objective necessarily has a low numerical aperture and consequently a lower resolving power, but it has the advantage of use with a standard hemisphere (13.5 mm radius). This objective is designated UM3 (Pl. 2, fig. 5). Leitz also makes one designated UM4, having a magnification of 30×. The resolving power of this objective is so low that its value is questionable.

Bausch & Lomb Optical Company has refused to produce an objective of resolving power equivalent to UM3 or UM4. Instead they make a 20× achromat to be used with a special hemisphere of smaller radius (7 mm) which is sold as a part of the objective (Pl. 2, fig. 8). The hemisphere is about half the size of the standard hemisphere. The objective therefore has a shorter working distance, a larger numerical aperture, and a greater resolving power. It has the disadvantage that it cannot be used with standard hemispheres. The operator may make his choice according to his needs. Both are desirable to have on hand. These objectives are equipped with built-in diaphragms whose purpose is to reduce the aperture when sharper extinction is needed. These objectives can be used with any Huyghenian ocular or with hyperplane or periplane oculars of magnification as high as 15×. This yields a total magnification of 300×. The stated magnification of these special objectives includes that of the hemispheres.

In studying the finer fractions of soils and in certain other studies still higher magnification was found desirable on the universal stage, and the objective UM4 was not suitable. At the writer's request Mr. L. V. Foster of the Bausch & Lomb Optical Company designed an apochromatic objective of 20× magnification including the hemisphere (Pl. 2, fig. 7). The hemisphere, sold as a part of the objective, is half (3.5 mm radius) the size of their special hemisphere used with their 20× achromat. The objective is equipped with a diaphragm. Like all apochromats, this objective is used with compensating oculars. Excellent results are available with a 20× ocular, and satisfactory results may be had with a 25× or 30× ocular; this therefore yields a magnification of 400× to 600×, sufficient for almost all geologic needs.

Small-aperture but clear interference figures may be obtained on the universal stage on crystals of average birefringence. Crystal fragments 0.3 mm in diameter, birefringence .009, yield good figures. However, one rarely finds it desirable to obtain an interference figure since the universal stage yields in routine manner all the information obtainable from a figure.

Chapter 3
Orientation Procedure

THE first step in orientation is to make α, β or γ parallel to the axis of the microscope—this opens several paths according to the type of information wanted. This first step on the four axis universal stage is done graphically with the aid of the stereographic projection, that is, the first setting of the various axes is obtained from the plot. To this extent the four axis stage is indirect and time consuming. After orientation, only one of the symmetry planes may be reached by direct rotation—the second step. These limitations have not, however, deterred the foreign workers.

On the five axis universal stage no graphical construction whatever is necessary to orient a crystal. Further, the oriented crystal, with only occasional exceptions when the inner stage is very steeply inclined, may be rotated in either of the two vertical optic symmetry planes of a biaxial crystal. This flexibility has the outstanding advantages of manipulation which will be brought out in the following pages, and it reduces the orientation procedure to a rapid and convenient preliminary.

Extinction is the optical feature employed in orientation. The essence of the procedure is this—1. Extinction reveals vibration directions. 2. Vibration directions are related to the planes of optic symmetry. 3. The planes of optic symmetry are adjusted to the cross hairs by rotating the crystal to and from extinction.

Of fundamental importance are two statements made earlier. For unaxial crystals—*One ray (the extraordinary) vibrates in the principal section, which is the section that includes the axis of the microscope and the optic axis of the crystal.* The ordinary ray of course vibrates perpendicularly to it. For biaxial crystals—*If the transmission direction (the axis of the microscope) lies within a plane of optic symmetry of a biaxial crystal, then the vibration directions of both rays which may be transmitted lie within optic symmetry planes.*

To Orient a Uniaxial Crystal: 1. On the inner vertical axis of the universal stage, turn the crystal to extinction. Then the principal section is parallel to one of the nicols, but it is not known yet to which one. Although it is possible that the optic axis is horizontal (or even vertical) the possibility is unlikely even in a crystal grain having good prismatic or basal cleavage. We may assume then that the optic axis is inclined to the axis of the microscope and to the stage of the micro-

scope, but we know that its trace coincides with one of the cross hairs.

2. Rotate several degrees to the east and to the west on the north-south axis, watching for a departure of the crystal from extinction. Similarly, rotate to the north and to the south on the outer east-west axis, observing extinction. On one of these rotations the crystal will remain at extinction. The axis of this rotation is perpendicular to the principal section and to the optic axis of the crystal.

3. Rotate, if necessary, 90° on the inner vertical axis in order that the crystal may remain at extinction on a rotation on the north-south axis. The optic axis then lies in the plane of the analyzer which is east-west on most modern microscopes. If the outer east-west axis is set at its zero position, then a proper rotation on the north-south axis makes the optic axis parallel to the axis of the microscope, and in the other direction perpendicular to the axis of the microscope. These positions are our objectives, but, since the crystal is already at extinction and extinction is our prime indicator, this step cannot be taken. With rotation on the outer east-west axis the crystal departs from extinction in the normal case since this removes the principal section from parallelism with the nicol.

4. Therefore rotate on the outer east-west axis to cause the crystal to leave extinction. This of course inclines the north-south axis, keeping it perpendicular to the optic axis of the crystal.

5. Rotate on the north-south axis either way to extinction which will be reached when the optic axis is parallel either to the polarizer or the analyzer.

6. Return the outer east-west axis to its zero position.

7. Rotate on the microscope stage. If the crystal leaves extinction, the optic axis is horizontal; if not, the optic axis is vertical. If the opposite orientation to the one desired has been thus obtained then repeat steps 4—6 but in step 5 turn on the north-south axis in the opposite direction to the one chosen to obtain extinction. Commonly either orientation is available.

Remove the analyzer—the ordinary ray is then transmitted in either case. A rotation on the north-south axis does not change the index since this axis is parallel to the polarizer. To obtain the extraordinary ray: (a) If the optic axis is horizontal rotate 90° on the microscope stage (or on the outer vertical axis). If this rotation was made on the outer vertical axis, then a rotation on the outer east-west axis changes the properties of the transmitted ray from those of the extraordinary toward those of the ordinary ray. (b) If the optic axis is vertical then a rotation on the outer east-west axis changes the

refractive index of the transmitted ray from that of the ordinary toward that of the extraordinary ray.

If the original objective is to make the optic axis parallel to the axis of the microscope the following orientation procedure may be preferred. Turn to extinction on the inner vertical axis. Test extinction on the north-south and east-west axes as before but, instead of making the crystal remain at extinction on a rotation on the north-south axis, cause it to do so for the outer east-west axis by a rotation of 90° on the inner vertical axis if necessary. The principal section of the crystal is then north-south. Now rotate 45° on the microscope stage, which causes the crystal to leave extinction. Next, rotate on the outer east-west axis to extinction. The optic axis of the crystal is now parallel to the axis of the microscope. This procedure has the special advantage that the outer vertical circle is now usually inclined making it possible to rotate on the outer east-west axis a full 90°. That is to say the crystal may now be rotated from its present position in which the optic axis is parallel to the axis of the microscope to a position in which it is perpendicular to the axis of the microscope. Such a step is especially useful in the determination of the carbonates whether in thin section or in liquid immersion as will be brought out later (Chapter 12). The frequency with which the carbonates are encountered in determinative work lends added value to this method. This procedure is also extremely helpful in that it conserves time when orienting a large number of uniaxial crystals for statistical purposes such as in the study of petrotectonics as described by Sander (1930) and others.

The sign of a uniaxial crystal is simply determined on the universal stage by means of the accessory plates as follows: Turn the crystal to the 45° position on the microscope stage, noting the position of the principal section. (If the optic axis is vertical, then rotate a few degrees on the outer east-west axis in order to incline it.) Insert the proper plate and note the standard effect on the interference color, indicating whether the ray vibrating in the principal section (the extraordinary ray) is fast or slow. In immersion work it is commonly easier to use the quartz wedge than the other plates except on crystals of very low birefringence, in which case the gypsum plate is preferred. In using the quartz wedge, observe movements of the interference color rings which are roughly parallel to the outline of the grain. Rings moving from the border toward the center of the grain indicate a drop in color; movement toward the border of the grain indicates a rise in color. This procedure may be chosen for grains which show any color above yellow of the first order.

As a corollary, the initial step of the orientation procedure serves as a rapid means of determining the uniaxial or biaxial character of a crystal. After turning to extinction on the inner vertical axis the crystal is tested for continued extinction on the north-south and outer east-west axes. If it remains at extinction on one of these rotations, it will usually prove to be uniaxial. For a biaxial crystal to do so would be a coincidence.

To Orient a Biaxial Crystal: The orientation procedure of these crystals is slightly more complex than for uniaxial crystals, though in part it is identical.

1. Turn the crystal to extinction. Though one or more optic symmetry planes may be vertical and parallel to a nicol, yet this would be a rare coincidence, even in a crystal of good cleavage (the micas excepted). We may safely assume therefore that the axis of the microscope is inclined to all optic symmetry planes, in which case we know that the horizontal traces of all three planes make angles with the cross hairs. We must learn next which plane is most steeply inclined and make that plane ultimately parallel to the analyzer. Although this is not essential, it results in a less steep inclination of the inner stage and is therefore desirable.

2. As for uniaxial crystals, test extinction by rotating on the outer east-west axis and on the north-south axis noting on which rotation the crystal departs least from extinction. If the crystal departs equally from extinction on both rotations then proceed with step 3. If not, then rotate 90° if necessary on the inner vertical axis to cause the crystal to depart less from extinction on a rotation on the north-south axis. We now know that one symmetry plane strikes roughly east-west and dips north or south but we do not know which way.

3. Incline a few degrees north or south on the inner east-west axis. Return the crystal to extinction on the inner vertical axis. Test extinction on the north-south axis noting carefully whether it departs more or less from extinction than it did before. If more, then reverse the direction of inclination on the inner east-west axis, return the crystal to extinction on the inner vertical axis, and once more test extinction on the north-south axis. By successive increment of inclination on the inner east-west axis, accompanied by returning to extinction on the inner vertical axis, and testing on the north-south axis, a position is found for the inner east-west and inner vertical axes, at which the crystal will remain at extinction when tested by wide rotations on the north-south axis. This procedure is neither lengthy nor difficult, though it is the most difficult step taken in orienting a biaxial crystal. It is essential that this step should be done carefully, as final

accuracy hinges mainly on it. The crystal is now so oriented that one symmetry plane is vertical and parallel to the plane of vibration of the analyzer. The other two symmetry planes are inclined to the polarizer, striking north-south and dipping one east and one west. Their line of intersection, which is the vibration direction of one critical ray, is horizontal and parallel to the plane of vibration of the polarizer and to the north-south axis. Therefore a rotation on the north-south axis would make one of the other symmetry planes vertical, but since the crystal is already at extinction and extinction is our criterion of orientation this step cannot yet be taken.

4. Incline several degrees on the outer east-west axis in the direction opposite to the inclination of the inner stage. This causes the crystal to depart from extinction, since the strike of the first oriented symmetry plane is parallel to the analyzer but the plane is inclined to the axis of the microscope.

5. Rotate to extinction on the north-south axis (now inclined). Commonly there are two possibilities, and the nearer one is chosen. The other leads to a different, but equally correct, orientation. The nearer one is chosen because it results in a less steep inclination of the inner stage.

6. Return the outer east-west axis to its zero position. The crystal is now critically oriented, two symmetry planes being vertical, one parallel to the north-south cross hair (the polarizer) and one to the east-west cross hair (the analyzer); the third is horizontal.

Both the north-south and outer east-west axes are horizontal, which makes it possible to rotate the crystal to search for optic axes in *either* of the two vertical symmetry planes. Also, it is an advantage to be able to make both these rotations in determining refractive indices in immerson work as brought out later. It will be shown too that this simplifies Berek's procedure for determining the optic angle indirectly. Further, the crystal has been oriented without accompanying graphical procedure. The universal stage with four axes of rotation does not have these advantages.

In orienting crystals of low birefringence, extinction is sometimes so indefinite that it is difficult to determine exactly. Under such conditions it helps to introduce the gypsum plate in which case the crystal when at extinction assumes the color of first order red. (The sensitive tint plate is still better but is not usually supplied with microscopes.) The eye can more easily detect a change from the first order red than a change from extinction. The oriented position is thus more accurately obtained.

Although the crystal is now so oriented that the cardinal directions are parallel to those of the microscope, yet it is not known which is which. To learn the answer we must identify the optic plane and determine the relative velocities of transmitted rays. The simplest procedure is best chosen first, failing which others may be employed. Turn 45° on the microscope stage. Then rotate widely on the outer east-west axis, searching for extinction. If extinction is found it indicates an optic axis position and defines the optic plane. If no extinction is found then set the outer east-west axis at zero, and with the microscope stage still at 45° test the crystal similarly by wide rotations on the north-south axis. Here too an optic axis position is revealed by extinction. The same result may sometimes be obtained more conveniently by rotating 90° on the outer vertical axis and then using the outer east-west axis instead of the north-south axis. If neither of these vertical symmetry planes contains an optic axis then the optic plane must be horizontal. In any of these cases the proper accessory plate may be introduced to learn which is the fast and slow ray, thereby identifying α, β, and γ.

One precaution should be taken to avoid a possible error. If the optic angle is small, the optic plane vertical, and the acute bisectrix horizontal, it may not be possible to reach the optic axis by a rotation on a horizontal axis. In this case it would be wrong to conclude that the optic plane is horizontal. Usually even if the optic axis cannot be reached the operator senses a small optic angle from the changes in interference colors and plans to use a check test.

Next the sign of the mineral may be determined. If an optic axis is found, then it is known immediately from the measured size of V which direction, α or γ, is the acute bisectrix. If the optic angle is near 90°, the measurements should be checked and carefully corrected. (*See* Chapter 4.) If the optic plane is horizontal, it may be possible to make it vertical by rotating 90° crystallographically on the north-south axis, that is, by rotating on the outer east-west axis, as was done in orientation step 4, and choosing the alternate extinction position of step 5 on the north-south axis. If no alternate position of extinction is attainable, another method must be used to find the acute bisectrix.

Berek's Method of Identifying Orientation: Berek (1923) learned that regardless of the position of the optic plane in an oriented crystal he could determine 2V and locate the acute bisectrix by rotating from an oriented position a known amount and applying the Biot-Fresnel rule. This rule states that the vibration directions of the transmitted rays of a biaxial crystal may be learned by bisecting

the angles made in a horizontal plane by the traces of two vertical planes, each of which includes one optic axis and the axis of the microscope, as indicated in Chapter 1. If the axis of the microscope lies in one of the symmetry planes the vibration directions lie in symmetry planes and are independent, in position, of the size of the optic angle. But if the axis of the microscope is inclined to the planes of optic symmetry the vibration directions (extinction positions) are dependent on the size of the angle 2V. If then from an oriented position we rotate a known amount we may deduce the size of the optic angle from the extinction position. Berek rotates the crystal from a cardinal orientation on two axes—the outer vertical and the outer east-west. Then he measures extinction in one direction on the stage of the microscope. This extinction angle is used as the ordinate of a graph in which the abscissa is the optic angle (Figs. 10, 11). Since there are three possibilities for the optic plane, there are three main divisions in the ordinate scale, one for each possibility, represented by 30° of rotation on the microscope stage. Further, for each possibility of the optic plane there are two possibilities for the position of the acute bisectrix. Therefore, in each 30° division there are two parts of 15° each. Accordingly the extinction angle tells us not merely the size of the optic angle but the position of the optic plane and of the acute bisectrix.

For this diagram the rotations are as follows:

1. Rotate 45° on the outer vertical axis from any one of the three oriented positions. This rotation may be made in either direction. If the inner stage is inclined steeply toward one of the 45° directions, one direction of rotation makes the inner stage incline east or west, which is undesirable, and the other direction of rotation inclines the inner stage north or south, which is to be preferred, as it permits a greater subsequent rotation on the outer east-west axis. This 45° position is to be borne in mind, as the interpretation of the figure refers to it. It is termed here *the reference position.*

2. Rotate 54.7° *(crystallographically)* on the outer east-west axis in either direction but usually in the direction opposite to the inclination of the inner stage. This rotation places the axis of the microscope equidistant from α, β, and γ—it is the angle between the poles of the cube (100) and the octahedron (111), α, β and γ representing the cube and the microscope axis the octahedron. In this symmetric position the vibration directions are so disposed that the extinction angles have a symmetric relation to the optic angle as may be seen in the 54.7° curve. Visualization of the change in position of the vibration directions may effectively be aided by folding a piece of

paper to represent three mutually perpendicular planes on one of which a variable optic angle is represented. By applying the Biot-Fresnel law the vibration directions may be located, and from them the extinction angle.

3. Rotate counter clockwise to extinction on the microscope stage and find the value so obtained on the ordinate of the graph. Follow across to the 54.7° curve which is the solid line. The abscissa indicates the value of 2V.

Note that the curve on which the ordinate reading made intersection indicates the attitude of the optic plane and the position of the acute bisectrix within it *for the reference position* of the procedure.

Limitations of this method are mainly that the results lack accuracy if the optic angle is small. If the acute bisectrix is horizontal there is no accurate method to measure a small 2V. If the acute bisectrix is vertical then this method would not be used as the optic angle would be measured directly.

This method is most valuable when the optic plane is horizontal. Commonly it is not possible to make the plane vertical, or if it is possible then a suitably wide rotation to search for an optic axis is not available. In such a situation the Berek method is invaluable.

A general purpose of great value, especially when the operator has become sufficiently accustomed to using the method so that the curves are fairly well committed to memory, lies in using this procedure immediately after orientation, to learn the position of the optic plane, of the acute bisectrix, the size of 2V, and the sign of the mineral, instead of using the methods already outlined unless the added accuracy of the standard method is preferred. This procedure offers a short cut, which is generally satisfactory to give the operator his bearings before proceeding with the details of any one of the subsequent studies. It is especially useful in studying our most common mineral, feldspar, in which the optic angle is rarely small. Even though the optic plane is vertical, it is commonly more rapid to use the Berek procedure than it is to search first one symmetry plane, then another, for an optic axis.

After completing the Berek procedure just outlined, although it is known which is the optic plane, the determination of 2V is not especially accurate, as pointed out, unless the rotation of 54.7° is properly corrected. Ordinarily the rotation O.E-W (54.7°) is only approximate since the correction necessary on account of the difference in index between the crystal and the hemispheres is usually estimated in the preliminary run. If the general index of the crystal is known then a degree or two may be added to or subtracted from the value
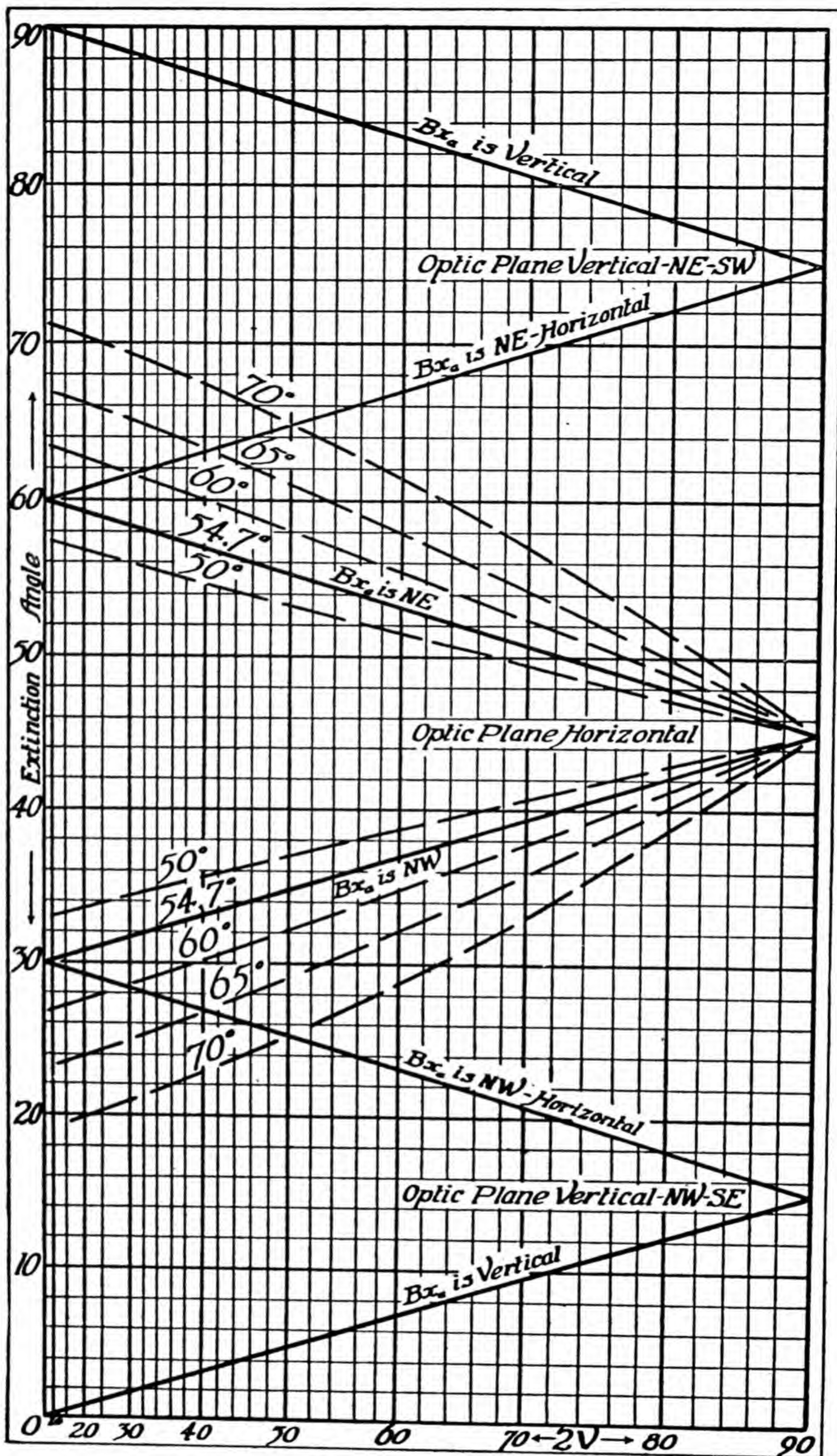
FIGURE 10.—*Berek (and Dodge) procedure*

This is especially convenient to use after the initial orientation of a crystal and as part of the orientation procedure. From the orientation secured, rotate 45° on the outer vertical axis and 54.7° (crystallographically) on the outer east-west axis. The counter clockwise extinction angle, which is the ordinate of the graph, gives on the solid line curve the attitude of the optic plane in the reference position (45° on O.V.), the position of the acute bisectrix, and the approximate optic angle.

If the optic plane is vertical the optic angle is read directly, if horizontal then instead of 54.7° (on O.E-W), the maximum value is used and applied on the broken line curves to obtain a more accurate measurement of 2V. The weakness of this method (as of all others) in measuring a small 2V is brought out in the scale of the abscissa.

54.7° according to the index of the hemispheres being used. (If the hemispheres are lower in index than the crystal then add, if higher, subtract.) For routine purposes this is adequate, but if a more accurate determination of 2V is needed the procedure may be modified in one of the following ways.

Make the rotation O.E-W truly crystallographic by determining the correction to be applied to the value 54.7 as described in Chapter 4. Rotate the corrected amount and then use the value of the new extinction angle M on the graph.

If the information obtained indicates that the optic plane is vertical then measure V or 2V directly as described under Orientation of Biaxial Crystals. This measurement is also to be corrected for difference in index between crystal and hemispheres as described in Chapter 4.

If the optic plane is horizontal, then a modification in the rotation O.E-W materially increases the accuracy. It will be possible quite commonly to rotate more than 54.7°, especially when the inner stage is already steeply inclined in the preliminary steps of orientation. It is not true when the inner stage is gently inclined after the crystal is oriented. Instead of rotating 54.7° (O.E-W) rotate as much as conveniently possible. Correct the indicated reading as described in Chapter 4. Determine the extinction angle M and find on the graph (Fig. 10) the intersection of the ordinate for the value with the proper broken line curve (O.E-W) already determined and corrected. This will usually be an interpolated curve. The abscissa then indicates the best value for 2V available under the circumstances—it should be ±2° unless the optic angle is small.

In the Berek procedure given, there are three fixed steps: (1) rotation O.V. which is 45°; (2) rotation O.E-W which is 54.7°; (3) rotation M which depends on the position of the optic plane and the size of 2V. Berek recognized this as a general procedure which in some cases would be accurate enough and in others would be a preliminary to indicate the proper steps for a more accurate procedure. To this end he provided other rotations to be used on other curves, a method which increased the accuracy. Dodge (1934) followed this lead and developed a systematic procedure with accompanying groups of curves making it possible to choose conveniently the most desirable rotations for each set of data. The broken line curves of Figure 10 are after Dodge. The details follow.

First make the three rotations O.V. (45°), O.E-W (54.7°), and M as in the preceding paragraphs. Figure 11, which indicates the attitude of the optic plane and the position of the acute bisectrix,

carries notations along the curves which refer the operator to the proper subsequent figures (Figs. 12-16). The position of the acute bisectrix is given for the reference position and is to be used for the next figure. If the acute bisectrix is vertical the 2V reading will
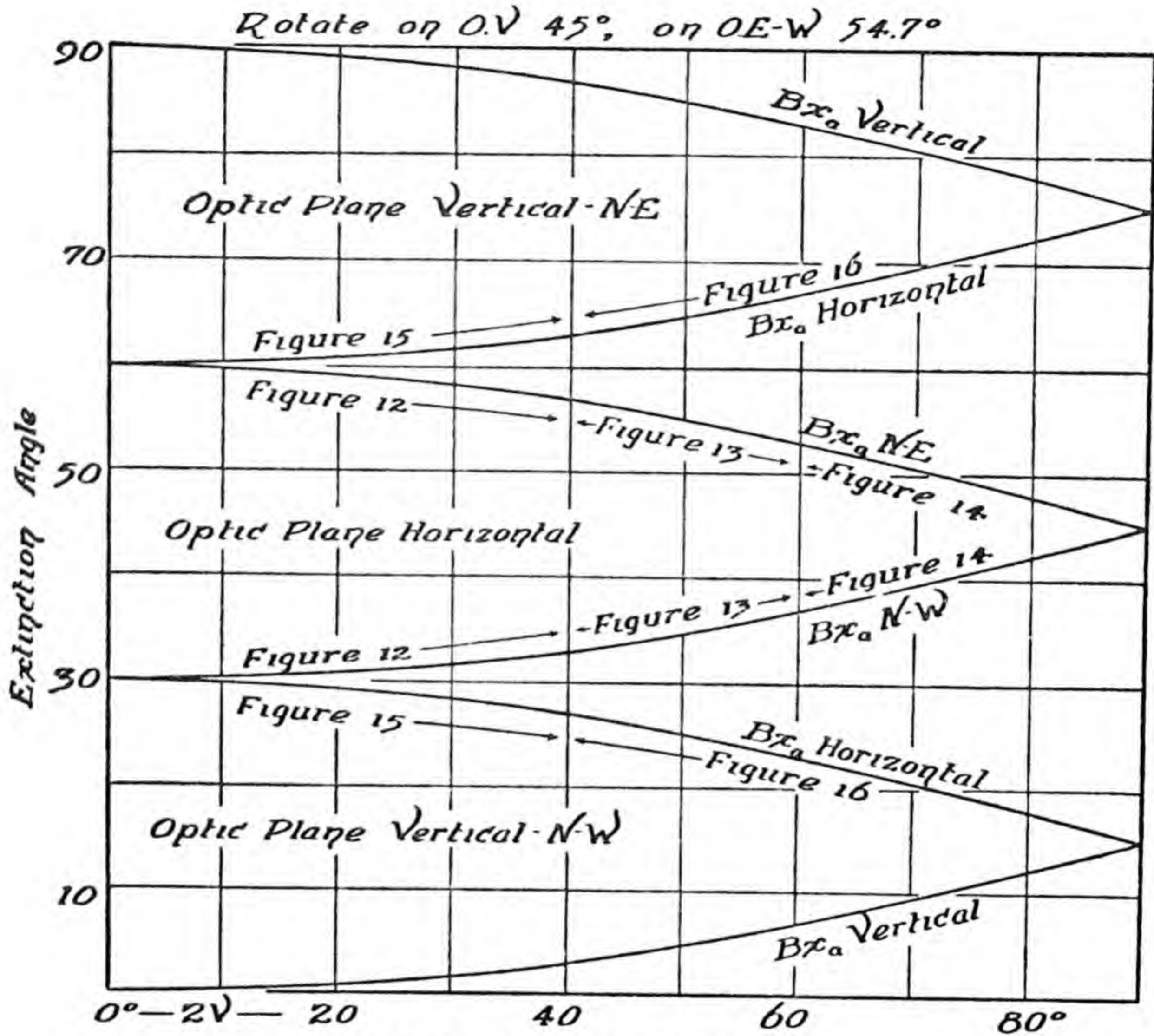
FIGURE 11.—*Guide to Figures 12-16*

Berek's original diagram for determination of orientation and optic angle indirectly. It is used here (following Dodge) as a finder for Figures 12-16. After orientation, rotate 45° on O.V., 54.7° on O.E-W, and counter-clockwise to extinction—the ordinate value. Locus of the point so found on this graph directs the next step for a more accurate determination of 2V to another plate —each of which has its own (quite similar) explanation. Common to each of these succeeding Figures are these instructions: (1) Acute bisectrix, identified here, is made north-south and the setting on the outer vertical axis, stated above each plate, is measured from this position. (2) Extinction angle, measured on the microscope stage, *must* be measured in the direction opposite to the rotation made on O.V.

be made by direct measurement. For all other positions of the acute bisectrix turn to the proper figure (Figs. 12-16) indicated. Set **M** and **O.E-W** at their zero readings. Adjust O.V. to make the acute bisectrix lie north-south. Above the plate is given the new value to be used for O.V. For the sake of uniformity it is well to *measure O.V. always in a clockwise direction*, in which case **M** will as before

be measured consistently in a counter-clockwise direction. The rotation O.E-W is usually made as large as the setting will permit, but the purpose is to use that curve or part of a curve which cuts the co-ordinates at about 45°. Knowing the approximate size of 2V
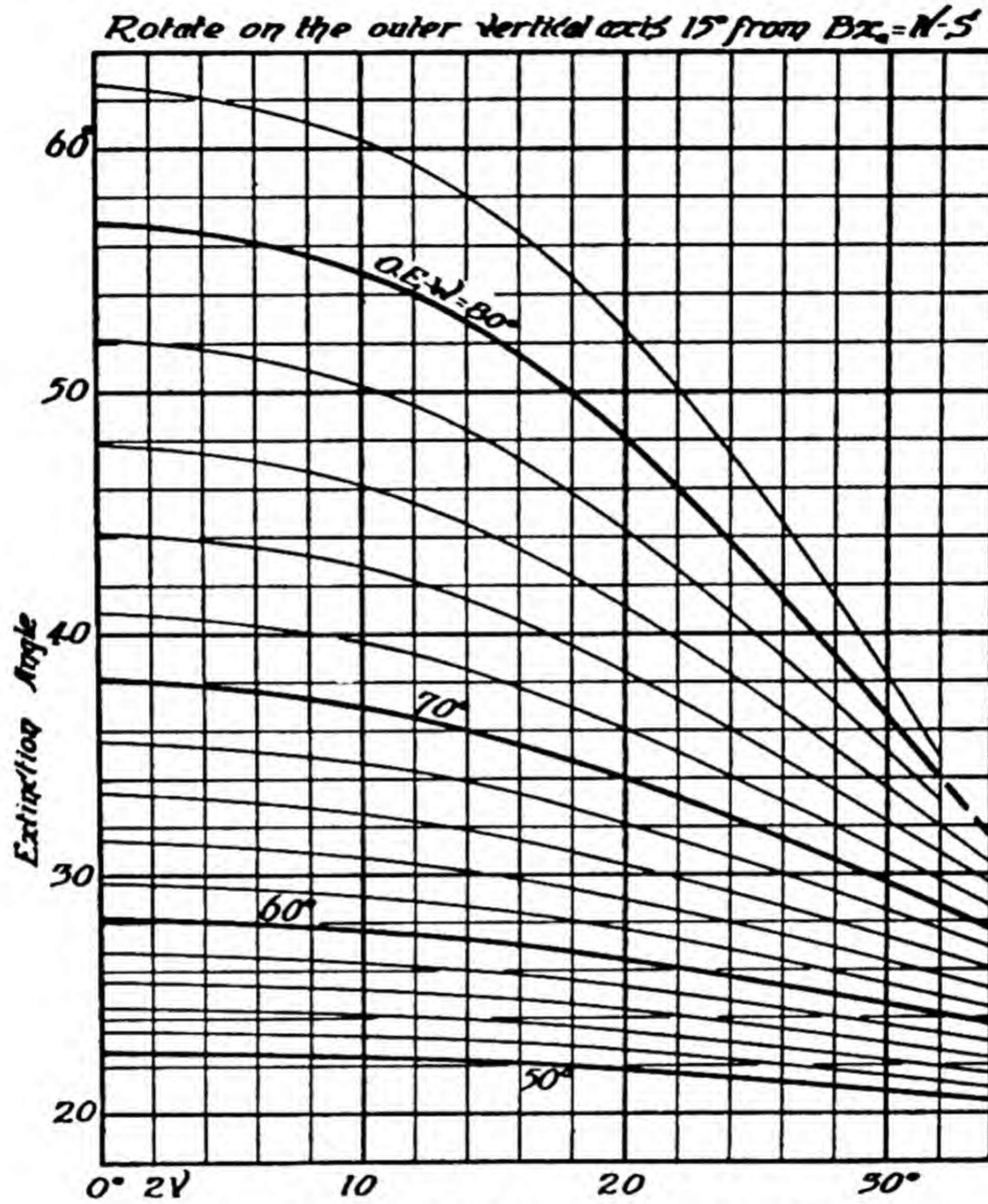
FIGURE 12.—*Dodge's curves for 2V*

Figure 11 has indicated that the optic plane is horizontal and the optic angle is between 0° and 30°. Outer vertical axis is rotated 15° in either direction from the position in which the acute bisectrix, identified from the use of Figure 11, is north-south. Outer east-west axis is set at a rotation value learned as follows: Knowing the approximate value of 2V from Figure 11, scan the curves directly above this value on the abscissa scale of this graph, choosing the one which most nearly cuts the co-ordinates at 45°. Set O.E-W at this value and measure the extinction angle on the microscope stage (M) in the opposite direction to that in which O.V. was measured. (Rotation on O.E-W is of course to be corrected, as always, for the difference in refractive index between crystal and hemispheres.)

the operator can select, by a glance at the figure, the most favorable curve. The rotation O.E-W is made to approximate the value for the curve.

Since the value of the rotation O.E-W is usually as large as possible, then when the inner stage is steeply inclined north or south

conditions are more favorable than when it is steeply inclined east or west (or is nearly horizontal) after rotating the proper amount on O.V. If it is nearly horizontal the setting cannot be improved, but if it is inclined toward the east or west after setting O.V. in a
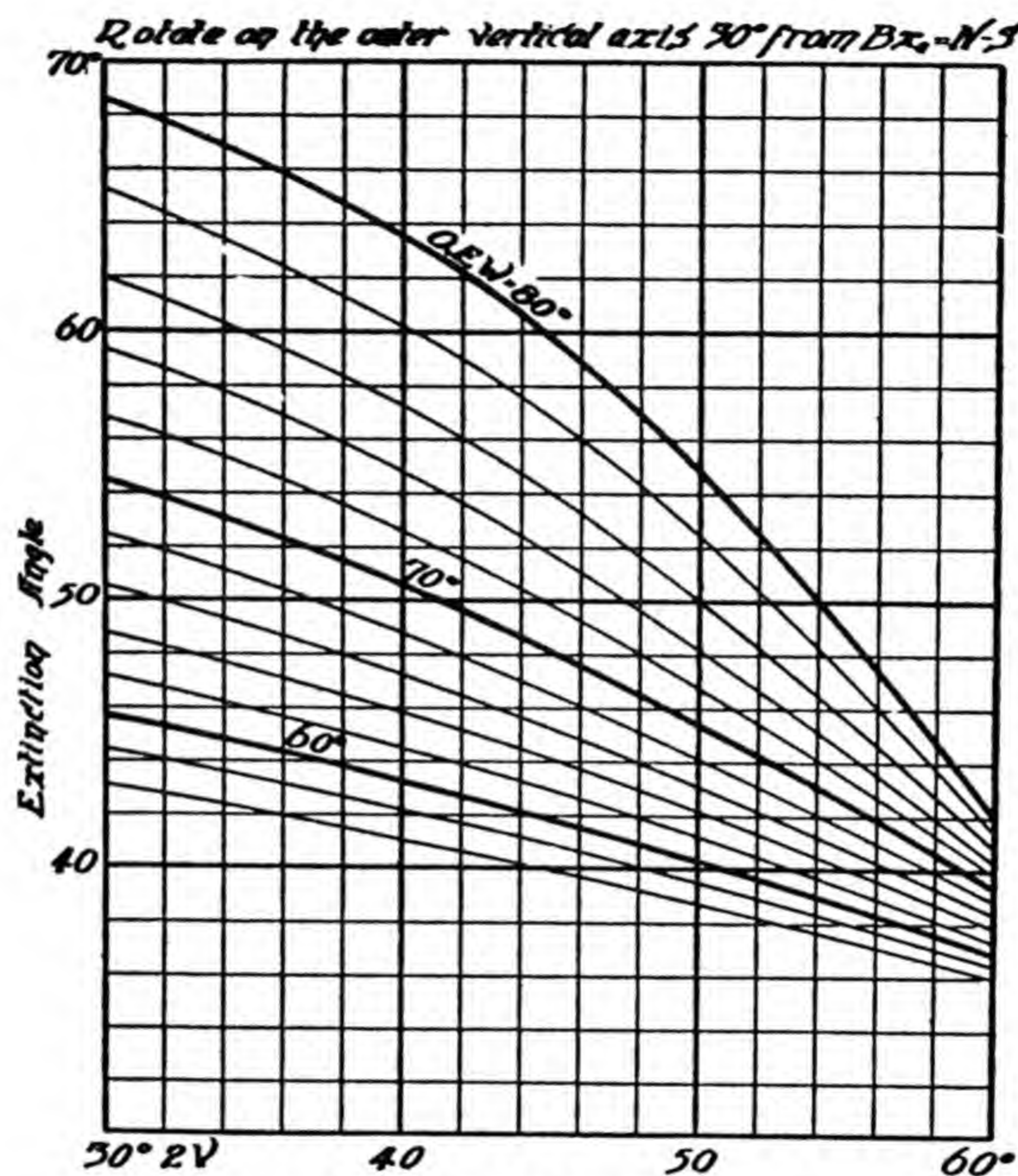
FIGURE 13.—*Dodge's curves for 2V*

Used when Figure 11 has indicated that the optic plane is horizontal and the optic angle is between 80° and 50°. Outer vertical axis is rotated 80° in either direction from the position in which the acute bisectrix, identified from the use of Figure 11, is north-south. Outer east-west axis is set at a rotation value learned as described in legend of Figure 12.

clockwise direction, as recommended above, this condition can be improved by rotating O.V. counter-clockwise thus permitting a greater subsequent rotation on O.E-W. Care must be taken however to remember that when O.V. is measured counter-clockwise the extinction angle M is to be measured in a direction opposite to that of O.V.

Once more since the crystal and the hemispheres do not agree in refractive index the rotation O.E-W is to be corrected. This may be done before making the rotation, but it is usually more convenient to do it later when making other corrections, and more is probably known about the refractive indices of the crystal. The corrected value

The Universal Stage

is then used on the chosen plate as an interpolated curve. The method of making the corrections is taken up in Chapter 4.

In work of this type it is always desirable to reduce the various steps to a routine which can be remembered easily. Such a routine
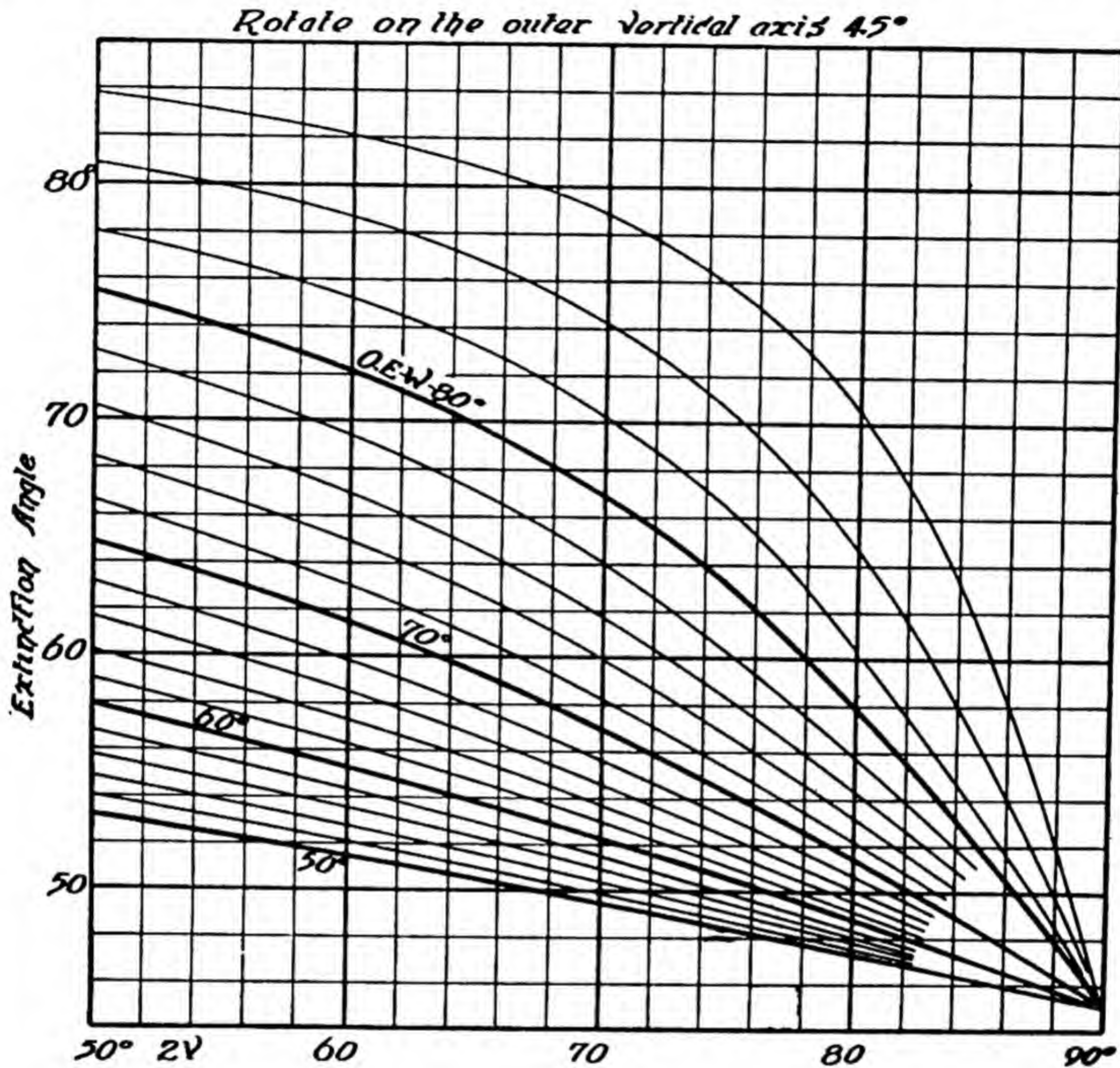
FIGURE 14.—*Dodge's curves for* 2V

Used when Figure 11 has indicated that the optic plane is horizontal and the optic angle is between 50° and 90°. Outer vertical axis is rotated 45° in either direction from the position in which the acute bisectrix, identified from the use of Figure 11, is north-south. Outer east-west axis is set at a rotation value learned as described in legend of Figure 12.

saves time and effort and does much to avoid errors since the operator's mind is on his main objective and the technique is merely a means to that end. Each operator should develop his own technique and routine procedure, but for the benefit of those who are being initiated to the use of the universal stage the following suggestion is offered: (1) Orient the crystal. By so doing the uniaxial or biaxial character is known. Assume the crystal to be uniaxial. (2) Rotate 45° on M, insert the proper accessory plate, incline on O.E-W if the optic axis is vertical, and determine the sign. The principal section is of course known from the orientation data. Assume next the crystal to be biaxial. (2) Rotate 45° on O.V. choosing to incline

the inner stage north or south rather than east or west.   (3) Rotate
54.7°, plus or minus an estimated correction based on a presupposed
general knowledge of the refractive indices of the crystal, on O.E-W.
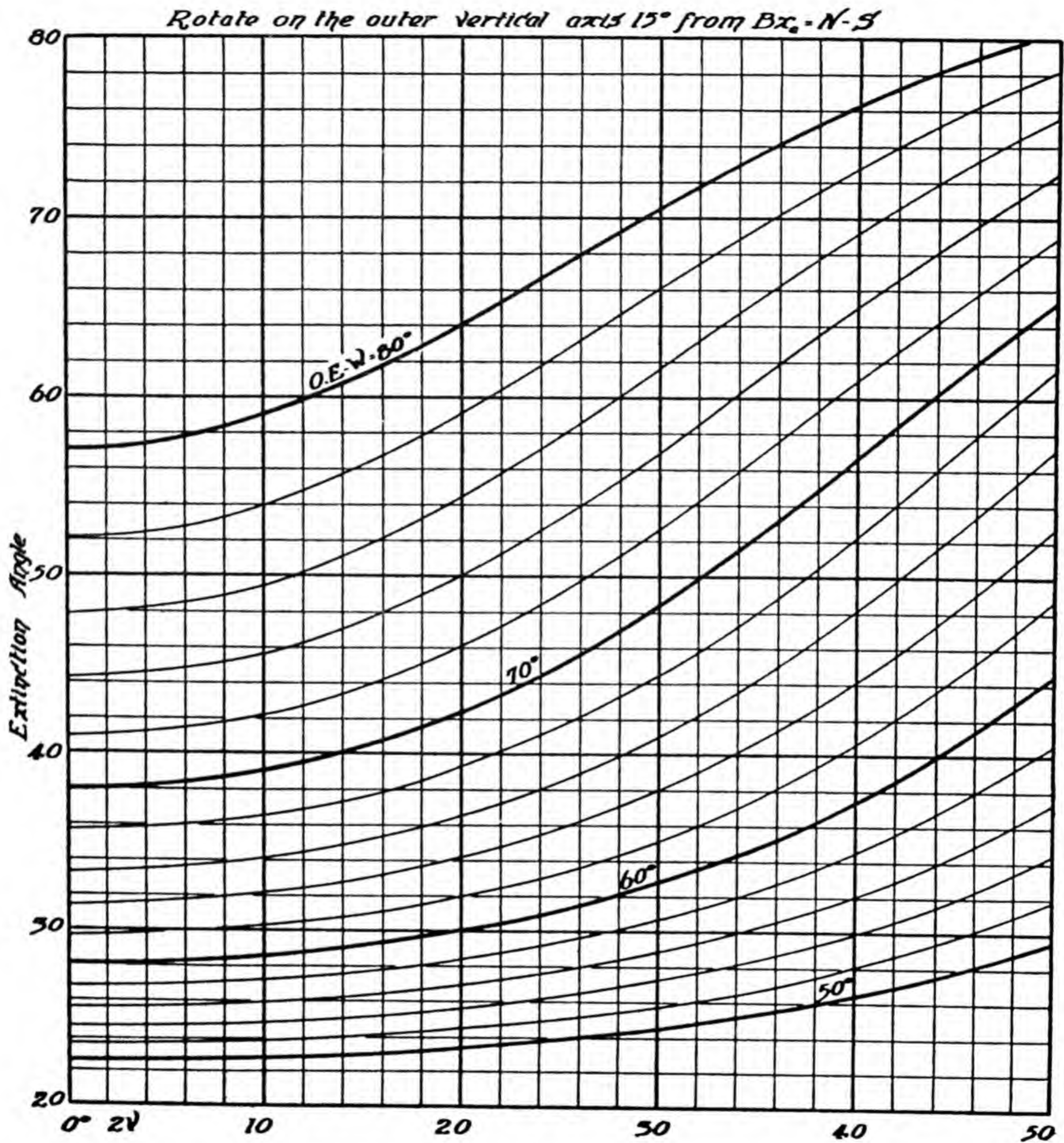
FIGURE 15.—*Dodge's curves for 2V*

Used when Figure 11 has indicated that the optic plane is vertical, the acute bisectrix
is horizontal, and the optic angle is between 0° and 50°.   Outer vertical axis is rotated
15° in either direction from the position in which the optic plane, identified from the
use of Figure 11, is north-south.   Outer east-west axis is set at a rotation value learned
as described in legend of Figure 12.

(4) Rotate counter-clockwise to extinction on M.   (5) Refer to Figure
10 or 11 to learn the position of the optic plane and the approximate
value of 2V.   (6) Return M and O.E-W to their zero readings and

insert the proper accessory plate to determine the sign. (7) **Refer** to Figure 11 to select the proper figure (Figs. 12-16) for a more accurate determination of 2V. (8) Follow the procedure for the chosen
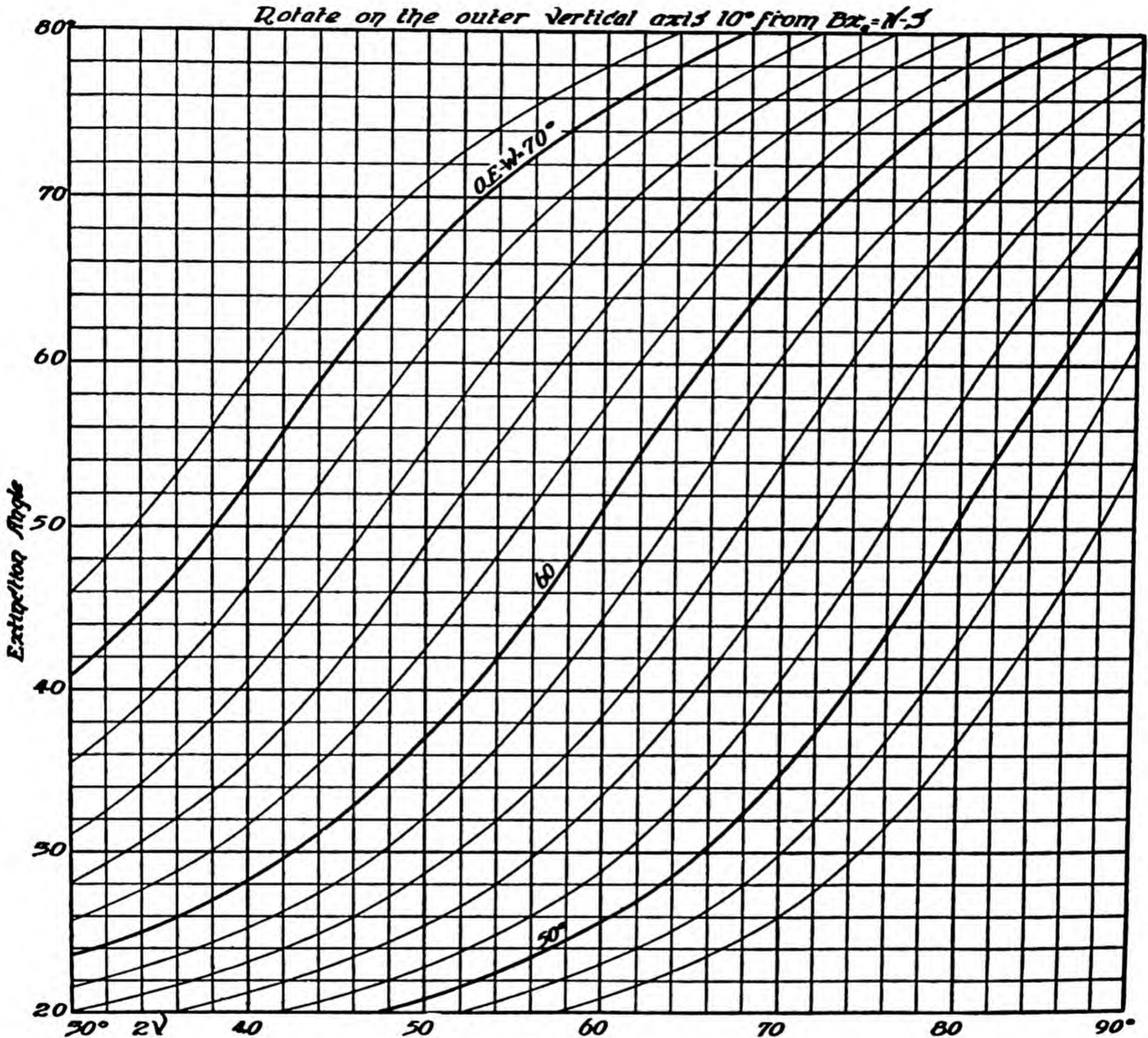
FIGURE 16.—*Dodge's curves for 2V*

Used when Figure 11 has indicated that the optic plane is vertical, the acute bisectrix is horizontal, and the optic angle is between 40° and 90°. The outer vertical axis is rotated 10° in either direction from the position in which the optic plane, identified from the use of Figure 11, is north-south. The outer east-west axis is set at a rotation value learned as described in legend of Figure 12.

plate as just outlined. (9) Return the crystal to its original oriented position.

Some systematic method of recording data is necessary both to avoid confusion and in the interests of accuracy. Forms are adopted

in the writer's laboratories. (*See* end of paper.) Some are used for thin sections, and one for an immersion mount.

It is unnecessary to use interference figures for universal stage work. It is impossible to obtain interference figures on the smallest crystals susceptible to study by universal stage methods since high numerical aperture objectives cannot be used. Crystals of average or higher birefringence which fill approximately one eighth of the field yield satisfactory interference figures which are sometimes helpful in locating the optic axis position more accurately. The low- or medium-power objectives standardly used are satisfactory in spite of their low numerical aperture. The swing-out condenser is not used of course, the hemispheres serving the purpose of moderate condensers. Nor is the angular aperture of the interference figure so large as that obtained with a high-power objective, but it is fully adequate. Since universal stage work is best done with an arc lamp or its equivalent, the back lens of the objective is by no means filled when using the Bertrand lens or removing the ocular. This is overcome by placing a frosted glass below the polarizer. Inexpensive accessory holders for a swing-out frosted glass slip over the polarizer as a cap. The field is then fully illuminated. As will be brought out later, this is routine procedure when using the universal stage as a refractometer (Chapter 11). In orienting crystals of very high refraction and birefringence, interference figures may be used to advantage as a final check on the accuracy of the orientation.

Chapter 4
Determination of Corrections for Rotations

IT has been shown in Chapter 2 that hemispheres reduce the change in the light path from air to a crystal when the inner stage is inclined. Without hemispheres light is refracted at inclined surfaces, toward the perpendicular, to reduce the inclination, and is in part lost by reflection. Although hemispheres are chosen to match the crystal in index, they never agree perfectly but require a correction to the apparent inclination of the inner stage to give the true inclination of the crystal plate to the light path in the crystal. If the hemispheres are lower than the crystal in refractive index, they require a minus correction to the apparent inclination of the inner stage; if the hemispheres are higher than the crystal, they require a plus correction to the apparent inclination (Fig. 6). We may speak of such corrected values, which tell us the true light path within the crystal, as *crystallographic* rotations or inclinations to distinguish them from the empirical values obtained from the scale readings of the instrument.

A given rotation of the mount results in a slightly different rotation of the light path within the crystal. Since we are primarily interested in the direction of the light path within the crystal the true direction must be learned. The crystallographic (true) light path may be calculated as the angle of refraction—from the angle of incidence, the index of the hemispheres and the mean index of the crystal, or better, from the index of the transmitted ray of the crystal. A diagram by Fedorow (Pl. 8) simplifies this calculation, based on the equation $N = \dfrac{\sin i}{\sin r}$ or more specifically $\dfrac{N'}{N''} = \dfrac{\sin r}{\sin i}$ where N' is the index of the first medium (hemisphere) and N'' is the index of the second medium (crystal).

Suppose for instance that the crystal has a refractive index of 1.60 and the hemispheres have an index of 1.65. For no inclination of the inner stage there is of course no correction or change of the light path within the crystal, but for an inclination of 50° the correction may be learned as follows. On the outermost arc find the value 50°. Follow the radial to the arc for 1.60, the index of the crystal. Then follow a vertical line to 1.65, the index of the hemispheres. The radial through this point indicates the rotation of the light path through the crystal (52.2°) from the position of no inclination. In thin-section study the estimated mean index is usually used. In immersion work

with the universal stage, the actual index for a given transmitted ray is used. The determination of the inclination may be studied next.

Occasionally an inclination is the result of a rotation in a north-south or east-west direction only, as in certain settings for uniaxial crystals. Such inclinations are read directly from the graduations on the instrument, and these values are corrected on Plate 8.

More commonly however the inclination of the inner stage is the result of rotations on several axes, and the sum of these is to be corrected. *At all times the angle sought is that between the perpendicular to the inner stage and the axis of the microscope.* If the perpendicular to the inner stage is regarded as the pole of a face the stereographic projection offers a familiar means of tracing the rotations. For this purpose Fedorow constructed a stereographic projection, here termed the universal stage protractor (shown in Figure 81 and in modified form in Plate 9), in which all possible cardinal rotations are given in divisions sufficiently small to enable the operator to read off rotations of known amounts with satisfactory accuracy. The purpose is to trace on this plate the various movements of the perpendicular to the inner stage which result from rotations on the several axes.

For example, suppose there are two rotations—30°N. on the inner east-west axis and 35° E. on the north-south axis. This is a typical setting for the orientation of a biaxial crystal. When the inner stage is horizontal the perpendicular to it is represented by a point at the center of the diagram. Therefore, follow the N-S cardinal line north from the center for 30°. Then follow the small circle, which is concave to the north, eastward for 35° counting on the great circles, which are concave to the west, and which pass through the north and south poles. The point so located is the position of the perpendicular to the inner stage after the rotations. The inclination to the axis of the microscope is now measured radially from the center counting on the concentric circles. This is the value (45°) to be corrected on Plate 8. Special attention is called to the order in which the two rotation readings on horizontal axes were measured on the protractor. If the order is reversed a different result is obtained. Since the inner east-west axis for which the reading was given is horizontal only when the north-south axis reads 0°, this reading must be measured first. To reverse the order is incorrect.

The gnomonic net is similar to the stereographic and though not so widely useful has the advantage that the great circles of the stereographic projections (concave inward) appear on it as straight lines, which are a little more easily used. Either the stereographic net or the gnomonic net may be used for making corrections since only the

central part of either is needed. It will be shown later that the gnomonic net cannot be used in studying twinning.

Simple though these projections are, by far the most common source of error in routine work lies in their use. It may be profitable to review a few salient manipulations. It is recommended that those who are not thoroughly familiar with the stereographic projection review in any standard text on mineralogy the elements of its construction and use before proceeding further.

1. A rotation on an east-west axis causes the perpendicular to the inner stage to follow the small circles (hyperbolas of the gnomonic protractor) which are concave outward to the east and west. The central one is a straight line. Measurements of these rotations are made on the stereographic protractor by means of the great circles which are concave inward and meet at the east and west poles. On the gnomonic protractor measurements are made by means of the east-west straight lines.

2. Similarly a rotation on the north-south axis causes the perpendicular to the inner stage to follow the small circles which are concave outward to the north and south, and measurements are made on the great circles which are concave inward and meet at the north and south poles. Or, on the gnomonic protractor, follow the hyperbolas which are concave to the north and south and measure on the north-south straight lines.

3. It is not necessary to make these graphical manipulations for rotations on an inclined axis.

4. It is frequently necessary to make rotations on horizontal axes which are neither east-west nor north-south. To do so, superpose the drawing on a second protractor, rotate the upper one till the desired axis is either east-west or north-south, and use the lower one. In practice, corrections for difference in index of crystal and hemispheres are made on a protractor such as that of Plate 9. Examples will be given in Chapter 5. The manipulations of twins are done on a fundamental circle of the same size, which is superposed on a protractor when such odd rotations are to be made. Examples will be given in Chapters 8 and 9.

5. To measure a rotation on a vertical axis, the point representing the perpendicular to the inner stage follows one of the concentric circles. Measurements of rotation are made by means of the radials.

6. To correct an angular rotation for index difference between crystal and hemispheres: Assume the values given above for an oriented crystal north 30°, east 35°. The perpendicular to the inner stage now

lies 45° from the center and on the 45° radial (Fig. 17). Assume the hemispheres to have an index of 1.649 and the crystal 1.60. Correct this inclination value (45°) on Plate 8; it is 46.8°. Plot this point on the same radial. To distinguish corrected from uncorrected points
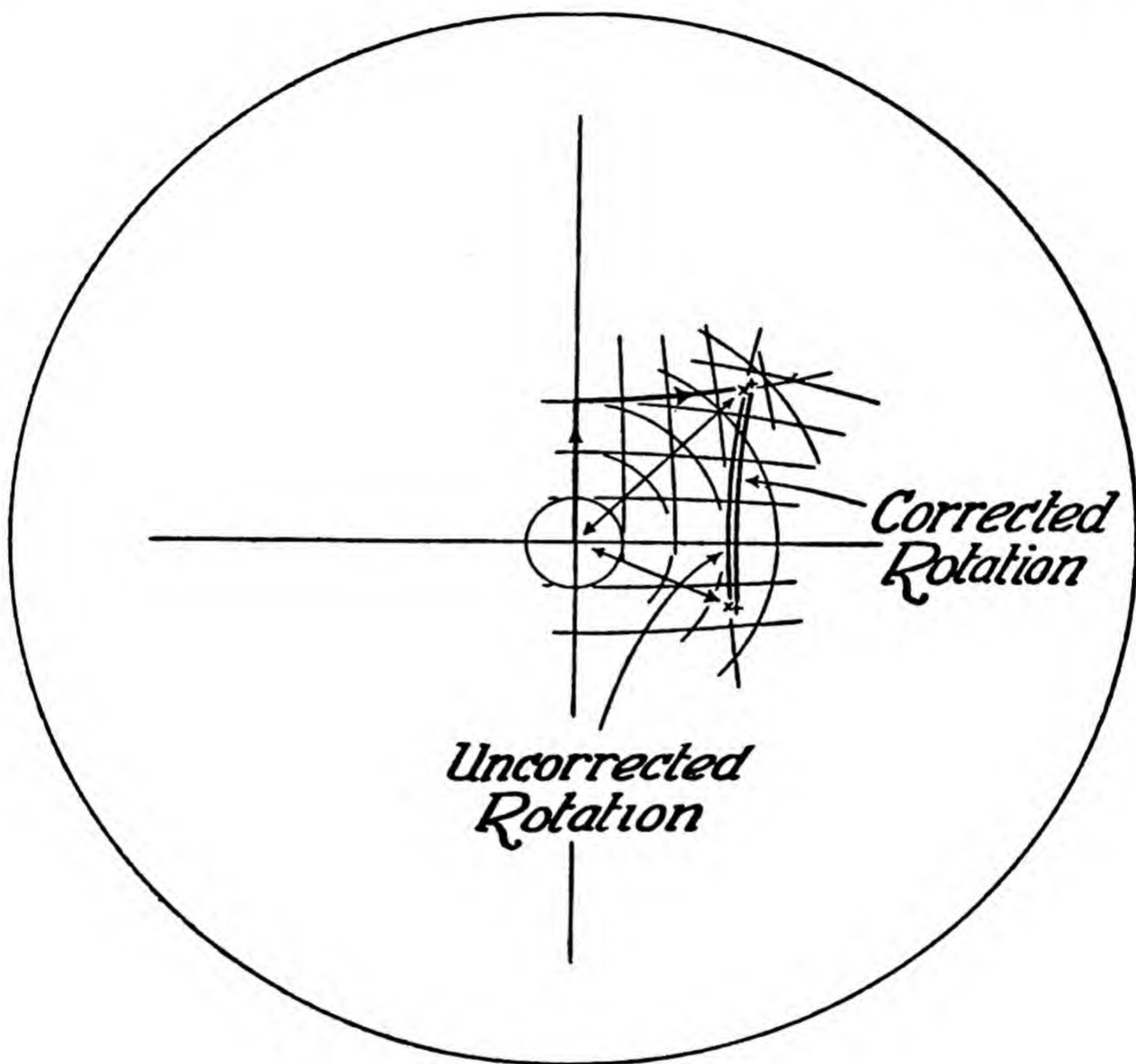
FIGURE 17.—*Principle of corrections*

Rotations on the instrument are not usually corrected directly since they are not often the angle between the inner stage and the axis of the microscope. This is instead to be found on the stereographic net. The rotations are 30°N, 35°E, and 50°S. The 50° rotation is to be corrected by first correcting the radial angles on Plate 8 and then measuring on the figure between the corrected points.

it is well to use a suitable symbol for each. In the illustrations, uncorrected points will be designated "×" and corrected points "+". Assume next a rotation of 50° on an east-west axis to the south. It is our purpose to correct this rotation. Measure on the east-west great circles 50° south from the *uncorrected* point, following an eastwardly concave small circle. The angular distance from the center now rests on the concentric circle 33°. Correct this value for index difference (using for convenience of illustration the same crystal

index); it is 34.2°. Plot this point on the same radial. The actual rotation of the light path within the crystal—that is, the 50° angle corrected—is now measured on the east-west great circles, *between the corrected points;* it is 52.5°.
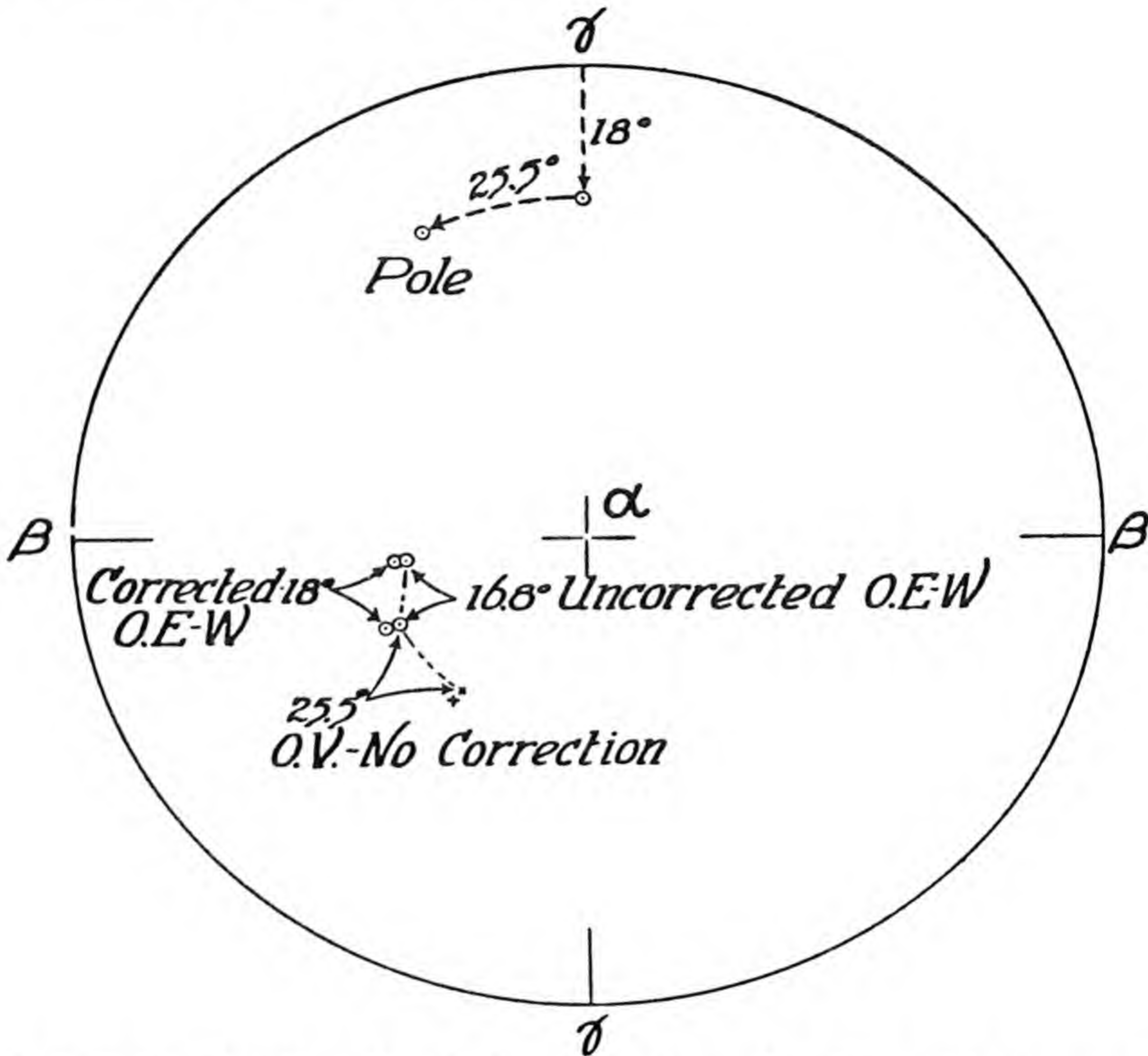
FIGURE 18.—*Location of pole of a crystallographic plane, with respect to optical orientation*

First correct the rotations made on the instrument as at the center of the figure, then reverse the corrected readings as at the north pole. The face was made parallel to the east-west cross hair. The data are I.E-W = 84.4°S, N-S = 80.2°W, O.V. = 25.5°J, O.E-W = 16.8°N.

7. To locate the pole of a crystallographic plane with respect to a given (usually optical) orientation: Assume a crystal to be oriented optically. A cleavage direction or crystal face is then made parallel to the axis of the microscope and to the E-W cross hair by rotating on the outer east-west horizontal axis and on a vertical axis on which the north-south axis is dependent—namely, the outer vertical axis. In this position the pole of the crystallographic plane is at the north and south poles of the protractor.

Suppose the optical orientation of a feldspar is obtained by the rotations 34.4° S (I.E-W) and 30.2° W (N-S). From this position a favorably situated cleavage plane is made vertical and east-west by rotating 16.8° N (O.E-W) and 25.5° clockwise (O. V.). Locate the
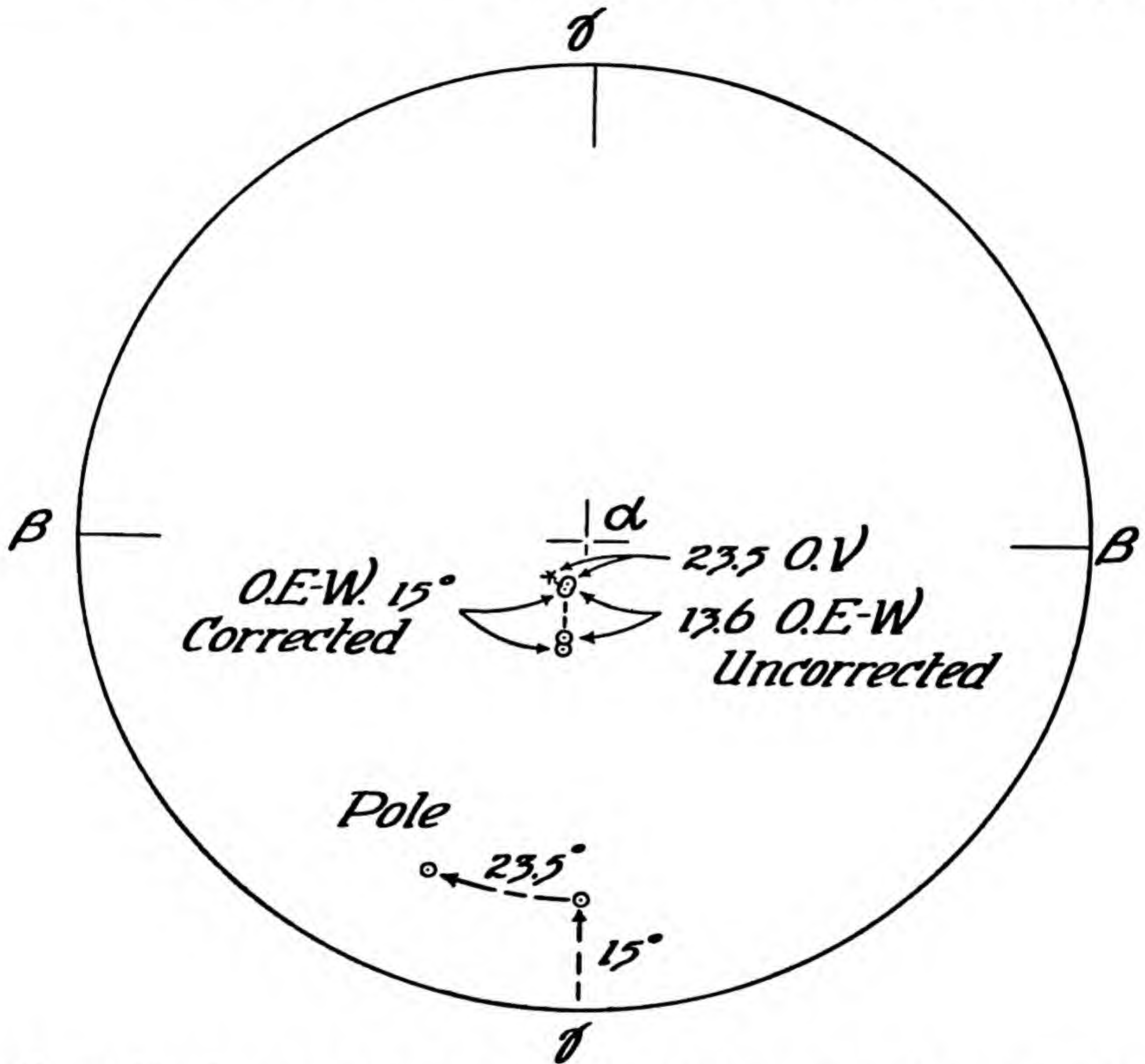
FIGURE 19.—*Location of a face pole when the face was made vertical and east-west*
Pertinent data are: I.E-W = 9°S, N-S = 8.5°W, O.V.= 23.5 ⌐, O.E-W = 13.6°S.

perpendicular to the inner stage for the oriented crystal. We shall first correct the rotations by tracing the movements of the perpendicular to the inner stage. These corrected values may then be applied to the pole of the crystallographic plane being studied. Since a rotation on the outer east-west axis inclines the outer vertical axis, we must trace the rotation on the outer vertical axis first. Therefore rotate the perpendicular to the inner stage 25.5° clockwise (Fig. 18). Correct the radial angle on Plate 8 and plot the corrected points.[5]

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[5] By a method to be described in Chapter 9, an approximate determination of the feldspar is already easily made; therefore, the mean index to use is learned. In these examples the mean is 1.565: Hemispheres 1.649.

Measure 16.8° north from this new *uncorrected* point (as described in #1 above) and correct the radial angle so formed. Now, between the *corrected* points at each end of the line representing the 16.8° rotation measure the angle—it is 18°. The value 25.5° of course
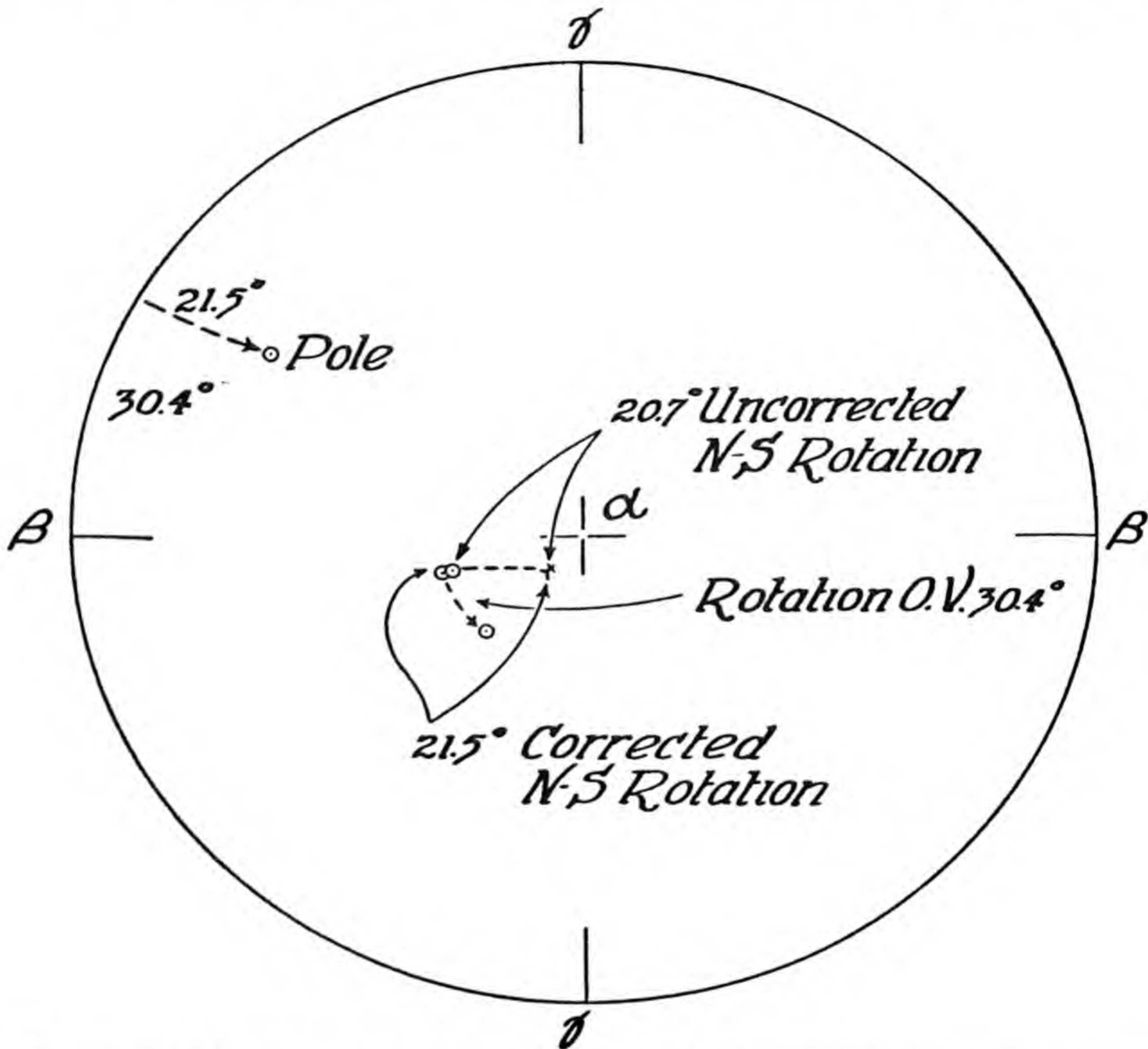
FIGURE 20.—*Corrections for rotations when the face was made north-south*
The data are: orientation—I.E-W 0°S, N-S 8.5°.W, and the face—N-S 20.7°W, and
O.V. 30.4° ↰ .

requires no correction. Knowing now the true crystallographic values of the rotations needed to orient the cleavage plane after the crystal is oriented, and knowing that the pole of the cleavage plane is north and south when oriented, it is now possible to trace the movement of the pole when the crystal is brought back to its oriented position. The former rotations are of course to be reversed to accomplish this. Therefore from the north pole measure 18° (the corrected value) south. This brings the outer east-west axis back to its zero position. Then measure counter clockwise 25.5°. This brings the outer vertical axis back to its zero position, and the crystal is once more oriented.

The point so located is the position of the pole of the cleavage plane when the crystal is oriented.

Figure 19 illustrates a variation in that the corrected data require starting at the south pole instead of at the north pole to plot the face pole. The data for orientation are 9°S, 8.5°W, and, to orient the face parallel to the east-west cross hair, 23.5° counter clockwise and 13.6°S. When a crystallographic plane is vertical and east-west the pole of the face is at both the north and south poles of the net. When the outer east-west axis reading is recorded to the south the measurement is made from the south pole since the reading is to be reversed to the north and may not be measured from the north pole. In both these illustrations the order of plotting the readings must be as shown.

The procedure in brief, then, is: Measure south (or north) the amount of the rotation on the east-west axis, corrected and reversed. Then following a concentric circle measure on the radials the amount of the vertical axis rotation, also reversed in direction. The point so found is the pole of the crystallographic plane when the crystal is oriented optically.

If, instead of making the trace of the crystallographic plane parallel to the east-west cross hair, it were made parallel to the north-south cross hair, the procedure would be a little different. The north-south axis and the same vertical axis are used, but the north-south axis is dependent upon the vertical axis. Figure 20 illustrates the procedure. A composition face of a twin in the same crystal used in Figure 19 and the same orientation was made parallel to the north-south cross hair and vertical. From the oriented position two rotations were used—20.7° W (N-S) and 30.4° counter clockwise (O. V.). Actually the reading on the north-south axis was 29.2° W, from which 8.5° W (the reading on this axis for the original orientation) must be subtracted. Correct the rotation on the north-south axis as outlined in #6 above. The rotation on the vertical axis does not enter in this correction, nor does it need to be corrected. The crystallographic rotations needed to orient the composition face are then, corrected, 21.5° W (N-S) and 30.4° counter clockwise (O. V.).

Since the crystallographic plane was so oriented that its pole was east-west, measurements are made from one of these points, in this case the west, to locate the pole in the oriented position of the crystal. Whereas in the last illustration the horizontal rotation reading was plotted first because the vertical axis O. V. is dependent on the horizontal axis, O.E-W, in this example the vertical axis rotation reading is plotted first since the horizontal axis, N-S, is dependent on the ver-

tical axis, O. V. As before, the readings are reversed in direction to bring the crystallographic plane back to the position it occupied when the crystal was oriented. Measure therefore from the west point, clockwise 30.4°, then eastward 21.5° along or parallel to the proper
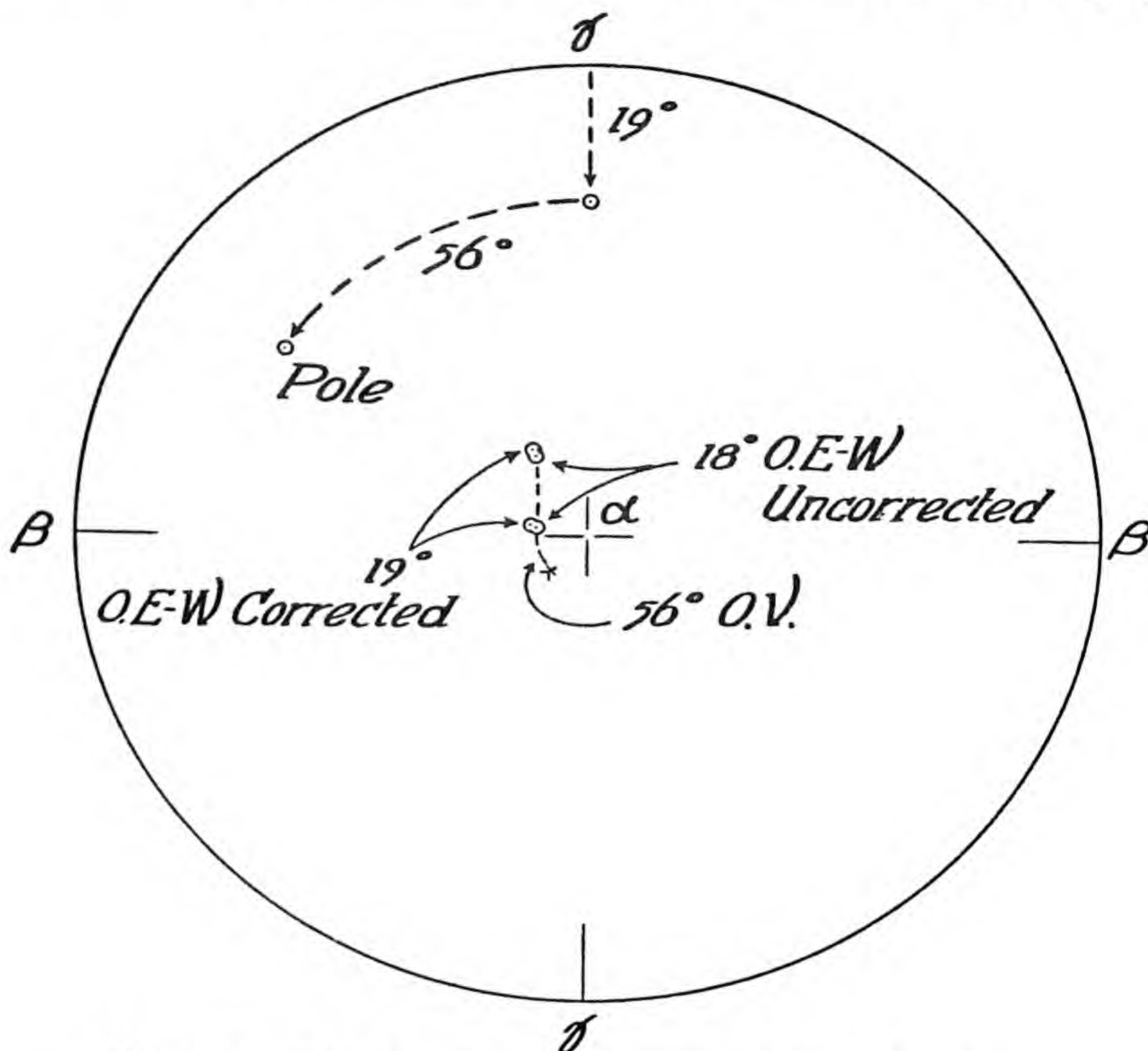
FIGURE 21.—*Same face pole as in Figure 20 oriented east-west*
Rotations corrected, and the pole located. The data are: orientation as in Figure 20, the face—O.E-W 18°N, O.V. 56° ͻ .

small circle. The point so found is the pole of the composition face when the crystal is oriented.

It is sometimes possible to use either combination of axes—namely, N-S and O.V. or O.V. and O.E-W—to make a crystallographic plane parallel to the north-south or east-west cross hair respectively. Usually when a choice is possible it is more convenient to use the axes O.V. and O.E-W by preference. Figure 21 illustrates the method of location of the same pole as that found by the procedure of Figure 20, but using the other combination of axes. The explanation of the figure is the same as that of Figure 18.

8. The method of finding an optic axis has been described—a direct rotation is made from a bisectrix to it. This value is V and when doubled gives 2V. If the hemispheres do not agree in index with the crystal and they rarely do, then this measurement too must be cor-
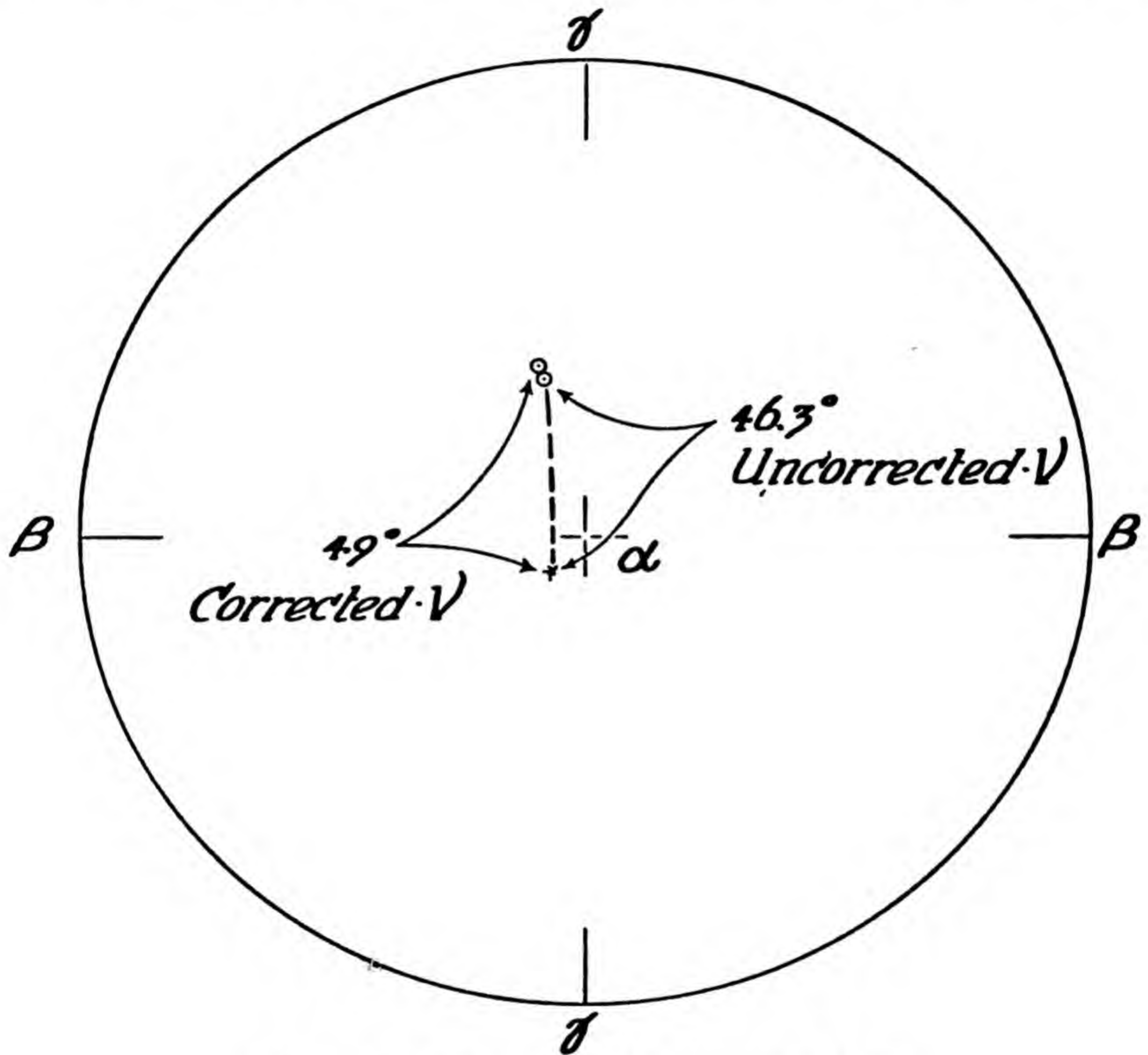
FIGURE 22.—*Procedure for correction of* V
Optic plane is north-south.

rected. Let us examine a typical case, illustrated in Figure 22. After the crystal is oriented a rotation of 45° was made on the microscope stage (M). Then a rotation was made to extinction on the outer east-west axis—46.3°N. This angle is V uncorrected. Locate on the protractor the perpendicular to the inner stage and correct the radial angle. From the uncorrected point measure north (as in #1 above) 46.3°. Correct this radial angle and plot the corrected point. Now measure the angle between the corrected points—it is 49°, the corrected value of V. Note that the rotation of 45° on the microscope stage does not enter into the correction since it does not in any way

affect the inclination of the inner stage. In other respects this example is similar to #6.

In studying thin sections the mean index is employed in using Plate 8. If the crystal is a feldspar this can be done with some degree of
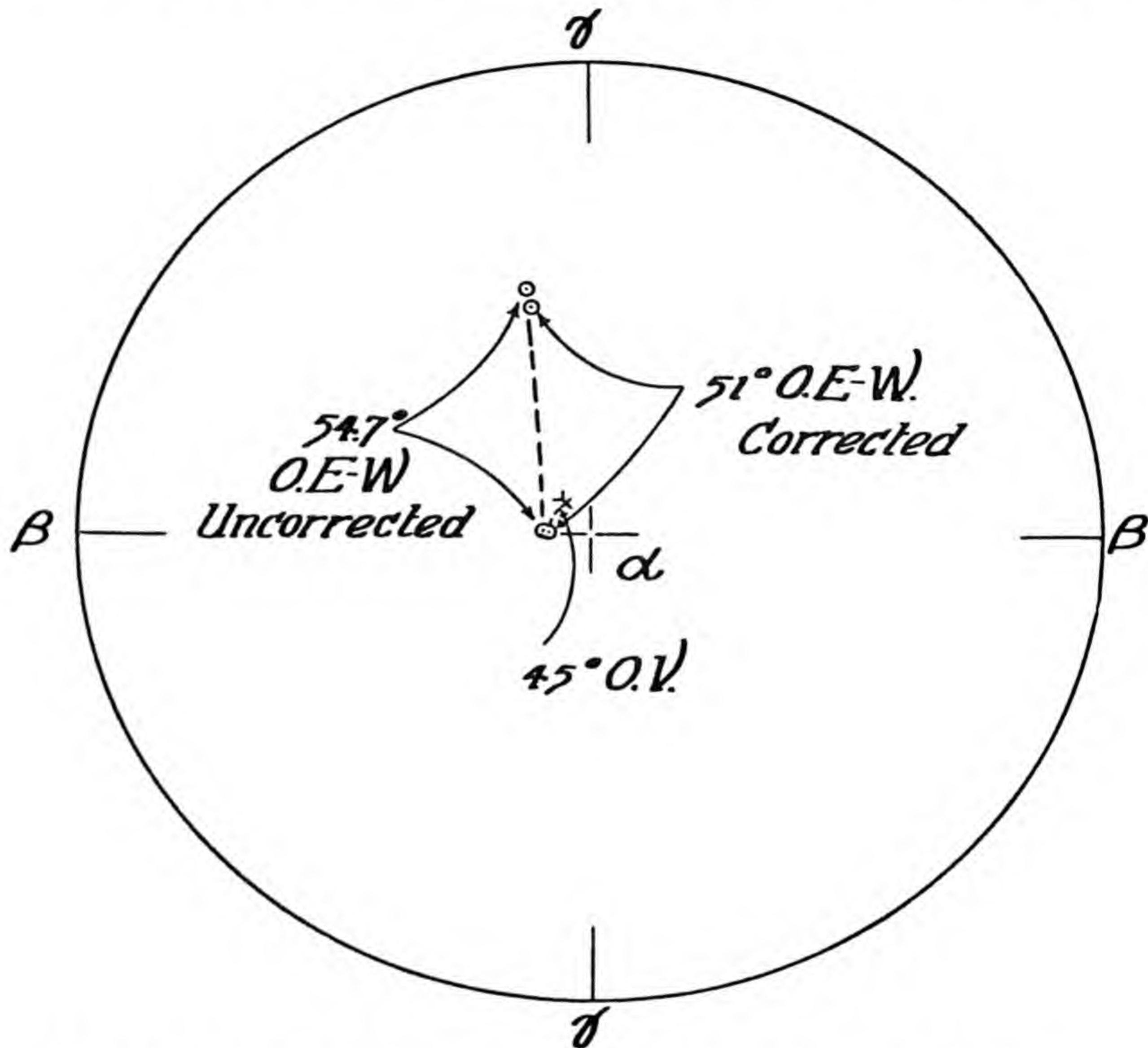
FIGURE 23.—*Method for making a crystallographic rotation of 54.7°*
In Berek procedure.

accuracy as will be brought out in a later section. If the crystal is one less thoroughly reported in the literature the estimate of the mean index may be more difficult, and accuracy is impaired. In immersion work, as will be brought out in the following chapter, the indices are well known usually, and the correct value is used for each inclination.

9. In the procedure of Berek, already discussed, the most common rotations are, from the oriented position, 45° on the outer vertical axis and 54.7° on the outer east-west axis. The value 54.7 is of course to be corrected. In practice the operator estimates the correction if he is able to estimate the mean index of the crystal, and usually he is.

This gives rough results, but usually since the main objective is to learn the details of orientation it is satisfactory. If the hemispheres are higher than the crystal in index, then rotate less than the required amount for a given rotation; if lower, then rotate more than the re-
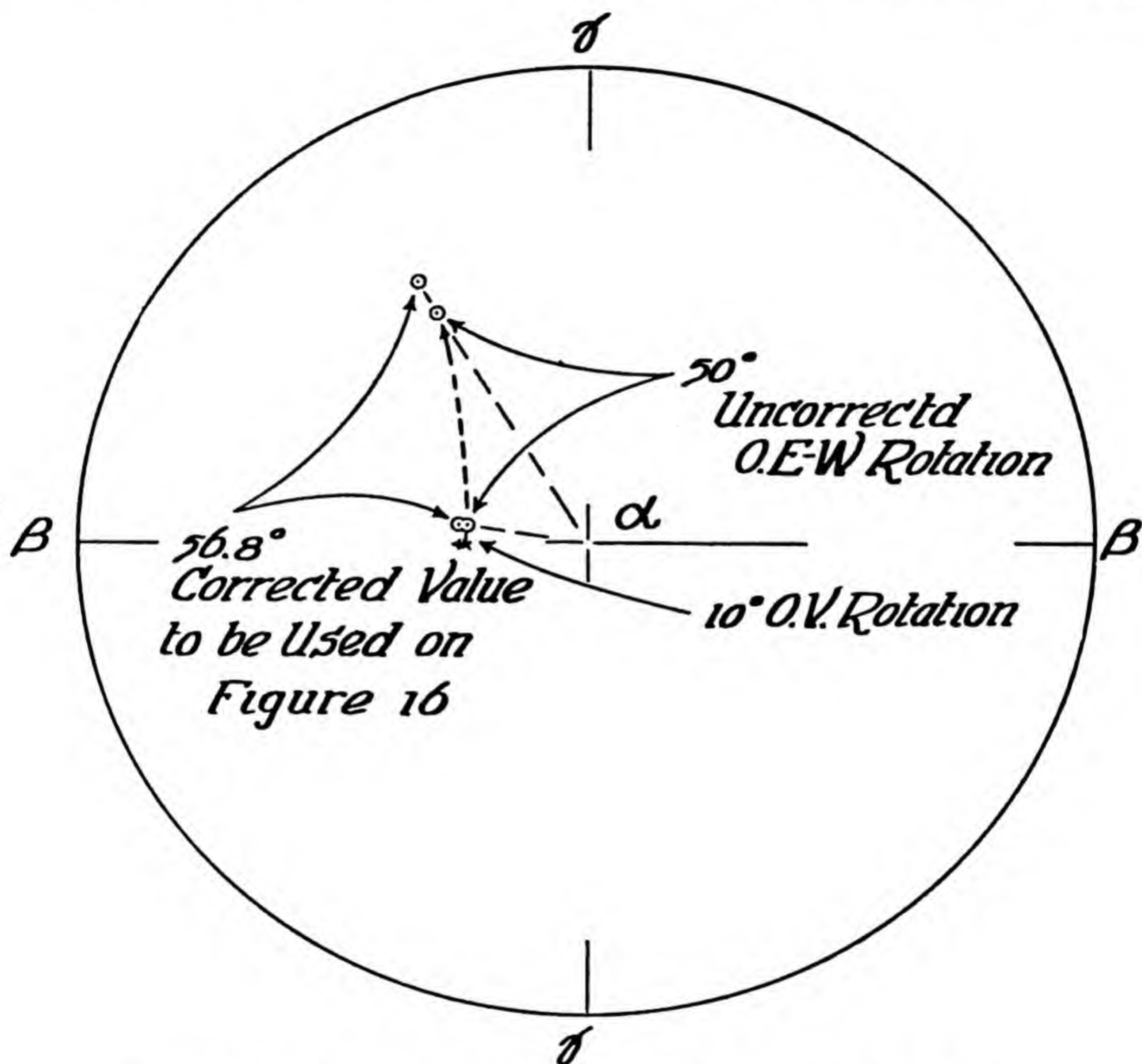
Figure 24.—*Correction for the Dodge procedure (Fig. 16)*

A rotation of 50° was made on the outer east-west axis, a value chosen after a preliminary use of Figure 11 and an examination of Figure 16. Before using 50° on Figure 16 it must be corrected, and the corrected value used.

quired amount. The amount more or less depends upon the index difference.

Sometimes, however, it is desirable to rotate accurately 54.7° crystallographically, in which case the rotation on the outer east-west axis must be corrected in advance. Figure 23 illustrates the method. The perpendicular to the inner stage for the oriented position is indicated by the appropriate symbols corrected and uncorrected. Both points are rotated 45° counter clockwise, the chosen direction. (The other direction would be equally satisfactory.) From the corrected

new position measure north (or south) 54.7°. This last point makes with the center a radial angle which is to be corrected on Plate 8 but in the reverse manner to those carried out thus far, since we are now starting with the true angle and finding the observed angle. Plot the
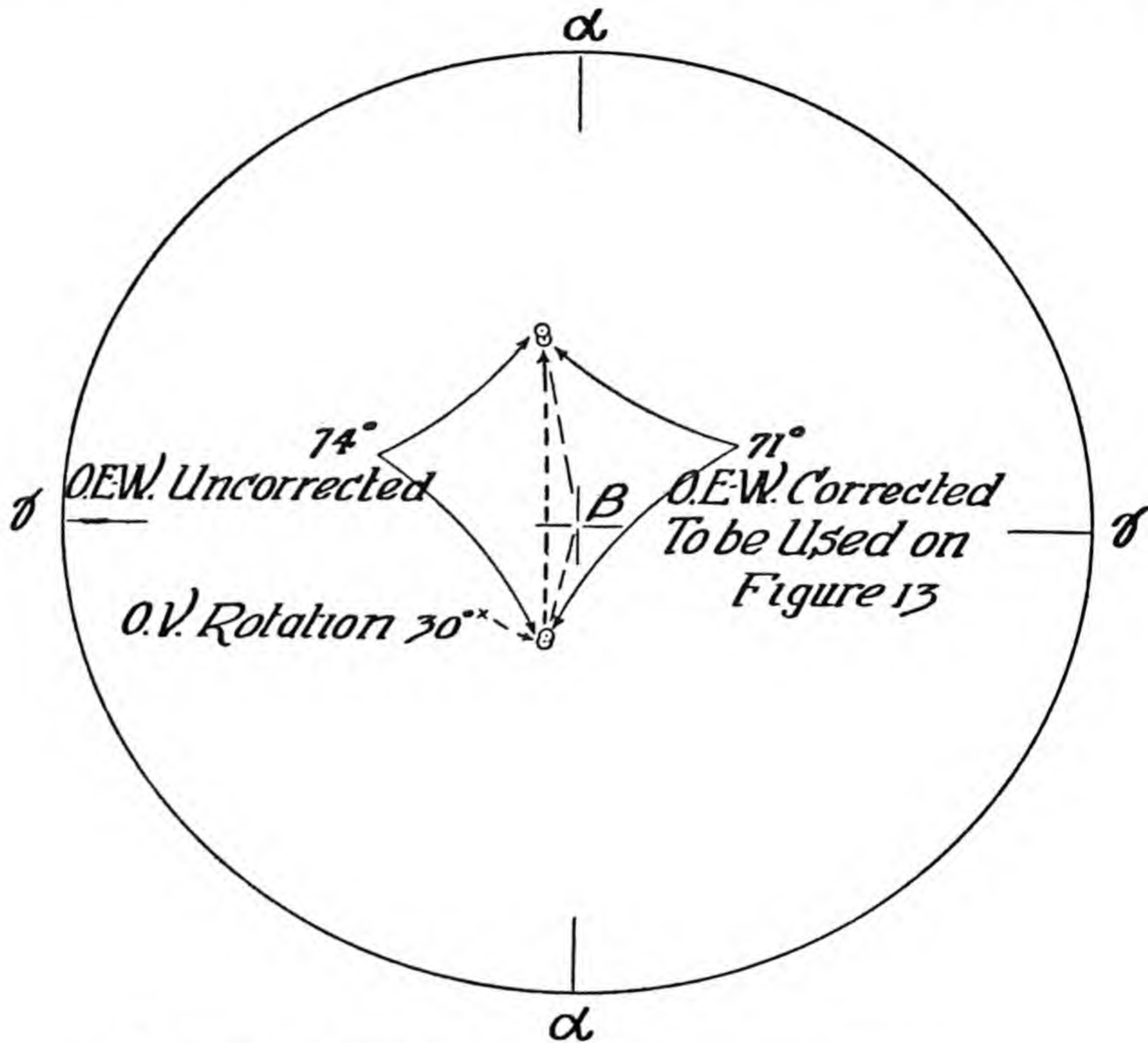
FIGURE 25.—*Correction for the Dodge procedure (Fig. 13)*

On the instrument as wide a rotation as possible on O.E-W is usually made when the optic plane is found to be horizontal. This value must be corrected as shown here before it is used on Figure 13.

"corrected" point which corresponds to those which we have been terming uncorrected. Now measure the angle between the last found point and the uncorrected point to the south. It is 51° and represents the amount to be rotated on the outer east-west axis which when corrected as in previous examples will be 54.7°.

10. The procedure of Berek just given (#9) is commonly preliminary to a more accurate succeeding procedure which has been improved by Dodge as discussed in Chapter 3. The corrections for the rotations of Dodge's procedure are entirely similar to those already

given, but we shall take up two examples, illustrated in Figures **24** and **25**.

(a) From the oriented position the crystal is rotated without corrections 45° on the outer vertical axis and 54.7° on the outer east-west axis, then to extinction on the microscope stage 19.5°. Reference to Figure 11 indicates that the optic plane is vertical and the acute bisectrix is horizontal, and that Figure 16 is to be used for an accurate determination. Reference to Figure 16 indicates that the outer vertical axis is to be rotated 10° from the position in which the acute bisectrix is north-south and that, for the value of 2V roughly learned on Figure 11 (70°-75°), a rotation of about 50° on the outer east-west axis is desirable since the 50° curve is suitably inclined. (Since the optic plane is already north-south in the oriented position it is not necessary to rotate first 90° on the outer vertical axis to make the acute bisectrix north-south.) The 10° rotation was made clockwise, therefore the rotation to extinction on the microscope stage was made counter clockwise—it is 61.5°. The rotation of 50° N on the outer east-west axis is to be corrected as shown in Figure 24. The corrected value is 56.8°. These two values (56.8° and 61.5°) used on Figure 16 indicate an optic angle of 73°.

(b) As in (a) Berek's preliminary procedure is applied to Figure 11—it indicates that the optic plane is horizontal, that the optic angle is 50°-55° and that more accuracy is available by using Figure 13. Figure 13 requires that the outer vertical axis is rotated 30° from a north-south acute bisectrix. The outer east-west axis is rotated north as far as possible for accuracy—in this case 74°. The microscope stage is then rotated to extinction in the *opposite* direction to the 30° rotation—in this case 45°. The 74° rotation, being on a horizontal axis, is to be corrected *before the value is used in Figure 13*. Figure 25 illustrates the method. The mineral is basaltic hornblende, the mean index used is 1.68, the correction, therefore, lessens the rotation. The corrected rotation, 71°, is applied to Figure 13 and the value of the optic angle is found to be 52° (the intersection of the curve for 71° and the ordinate (M) 45°—the abscissa 52°).

Examples of corrections made for immersion methods differ only in that the mean index is not used, but specific known indices of transmitted rays. This will be discussed in Chapter 5.

Chapter 5
Double Variation Procedure for Refractive Index Determination

ALTHOUGH thin sections yield information which cannot be otherwise obtained, the powder or immersion method of identification by means of refractive indices is popular in some laboratories almost to the exclusion of thin sections. Two reasons are: (1) A thin section is less readily prepared. (2) Too many thin-section methods for identification depend on specific orientation. Except for the most common minerals and crystals the usual extinction-angle determination fails to inspire enough confidence. The identity of a relatively rare crystal in thin-section may remain in doubt unless the universal stage is employed. For these and other reasons the powder method is preferred for identification of unknowns. The thin-section continues to reveal paragenesis.

Since identification itself is such an important part of routine petrography both quantitatively and as a basis for interpretation, it is most pertinent to speed up the technique by any means possible, especially that of an accurate determination. (The hurried 5-minute estimate which has its place in some types of work does not fall within the scope of our present interest.) It is also desirable to increase the accuracy of the general determination as practiced today, for two important and mutually dependent reasons. Granted suitably accurate and systematized data in a given mineral family, only suitably accurate and complete data on an "unknown", within the family, will yield the maximum information desired on the details of composition. Until more accurate data are collected on a wider variety of materials we cannot derive the maximum benefit from current studies of unknowns as there are few families now known as thoroughly as modern accurate methods make possible. Accurate optical data on chemically understood material is our greatest current need in the field. We are concerned here with accurate optical data, rapidly and conveniently obtained.

It is assumed that the operator is familiar with the principles of "powder" or "immersion" methods as outlined in texts on the elements of optical crystallography, and with the valuable modifications of Tsuboi (1926). We shall add to the procedure certain other modifications which greatly increase the accuracy of this, our most popular method of identification, at the same time requiring much

less time than has been otherwise needed for accuracy and little more time than the hurried guesses that we use in much of our work.

In routine work with white light, successive mounts are made until for each critical ray a liquid is found having an index to match the ray, at least approximately. The index of each liquid is then determined. Since the liquid has a fixed index the value for the ray is

FIGURE 26.—*Water cell for the microscope stage*
This cell has relatively heavy glass windows and is therefore sturdy.

usually stated as between the indices of the liquids used. In this method each figure represents a mount and is usually the result of several mounts and sometimes mounts of carefully mixed liquids.

Since the refractive index of a liquid varies with the temperature of the liquid (lower for higher temperature and higher for lower temperature), by varying the temperature of the mount under controlled conditions the index of the liquid may be given a considerable spread. Alling (1923) first made practical use of this principle in America by employing an electrically heated stage. Gaubert (1922), however, used hot immersion media which he studied as they cooled in contact with unknowns. The principle is the same. An average liquid changes refractive index .0003—for each degree Centigrade change in temperature. Most crystals change only a small fraction of this amount. By selecting a set of liquids having a high temperature coefficient of refractive index the change may be made greater —.0004 to .0007. This gives a change in the refractive index of a liquid, for a 50°C. range of temperature, ranging from .020 to .035. The same temperature range affects the refractive index of most of our crystals less than .0002, which is negligible. If the crystal and liquid do not quite agree in refractive index, they may be made to do so by varying the temperature of the mount in the proper direction. There is a water cell accessory to the universal stage (Pl. 2, figs. 1, 3, 4) designed to make this temperature variation conveniently possible. Another cell shown in Figure 26 is used on the microscope stage in the same manner as a glass slide. It makes

the control of temperature possible but affords none of the other advantages of the universal stage. This cell, as illustrated, is too thick to permit the use of interference figures. The statistical method of Tsuboi may therefore be used or the method of selecting grains
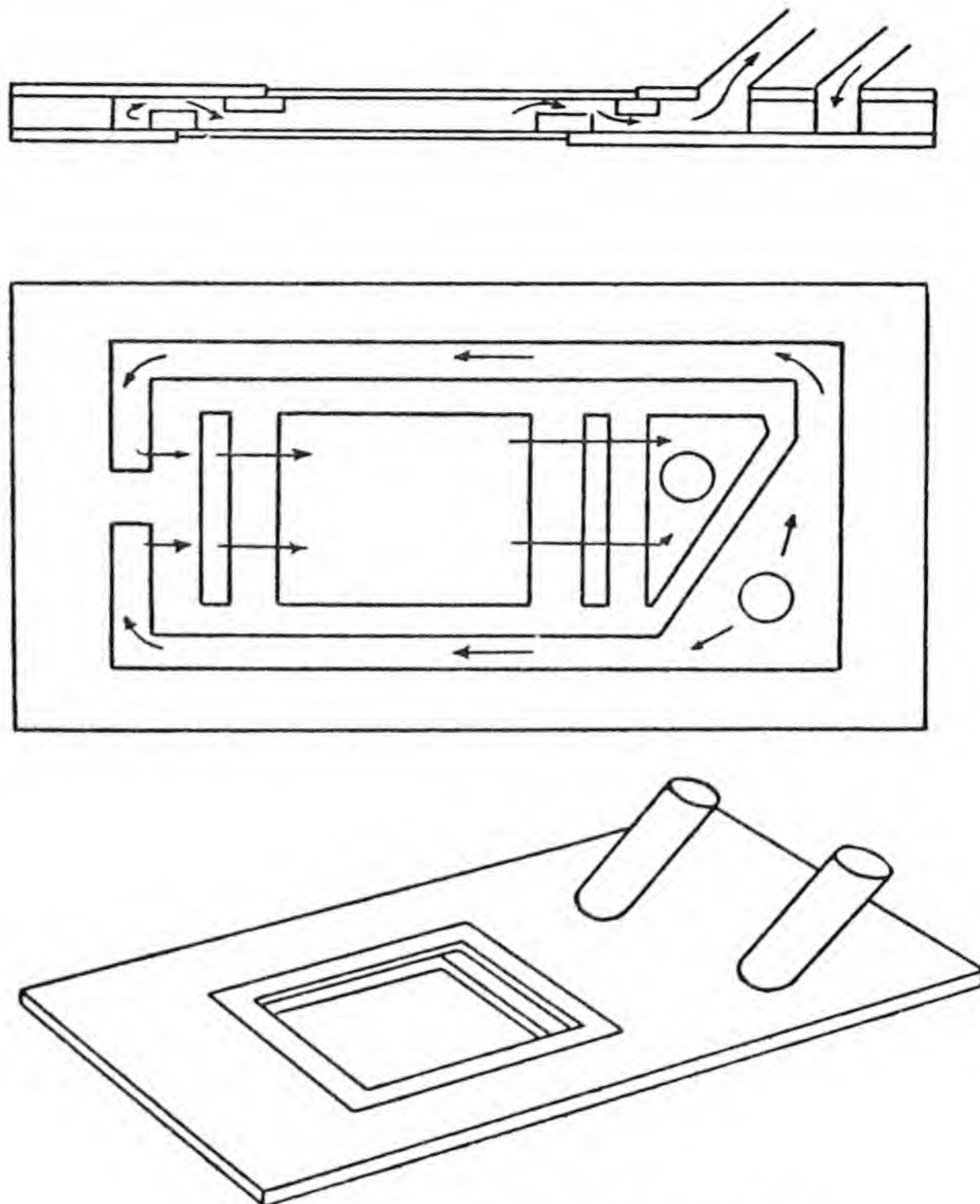
FIGURE 27.—*Saylor's design of thin cell*
With cover glass windows to make possible the study of interference figures.

of lowest (β) and highest (α and γ) interference colors. C. P. Saylor (1935) has described a cell which is thin enough for conoscopic study of grains (Fig. 27). This use of interference figures makes the recognition of accurately oriented grains more certain and is a distinct advantage over the cell shown in Figure 26. Neither method however obviates the difficulties encountered in the study of grains with cleavage. Saylor's cell is made of three plates soldered together. The top and bottom plates have windows which are slightly staggered, as shown in the cross section of the figure, and into which

cover glasses are cemented. The center plate directs the water flow as shown.

Saylor's cell is somewhat difficult and therefore expensive to make. Another model (Fig. 28) which embodies the desirable features of
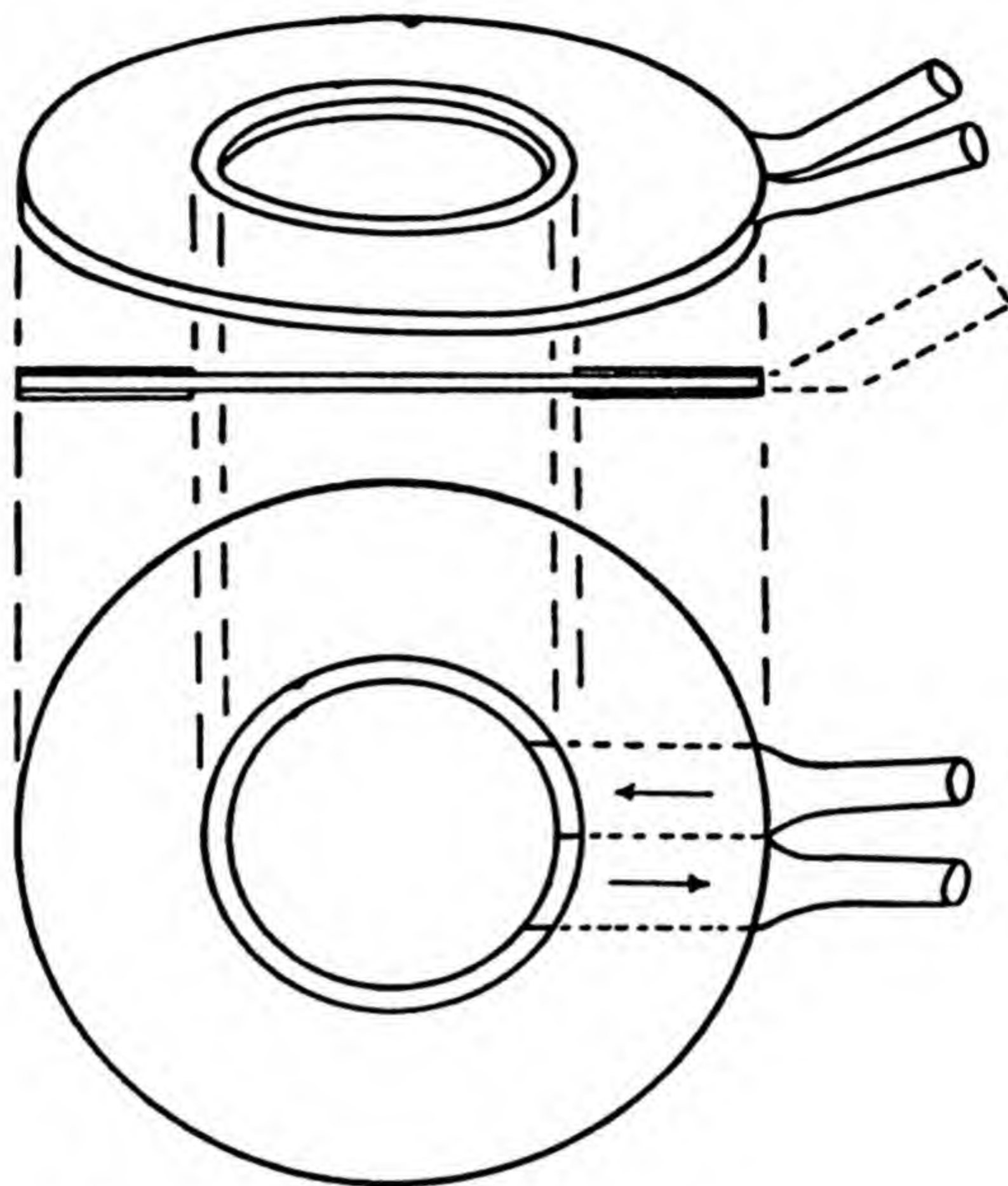
FIGURE 28.—*Hipple's thin cell*
After Saylor, using cover glass windows.

Saylor's cell, but which is much simpler in design, was developed by J. S. Hipple, mechanician at the University of Wisconsin. It too consists of three plates into the central one of which are fitted two flattened brass tubes which serve as nipples. Round cover glasses are fitted into the openings giving a total thickness equivalent to a glass slide.

All the cells tend to trap bubbles. This, though inconvenient, is not serious since the bubbles usually spin in one part of the cell only, and the mount may be made in another part. However, Vigfussen (1940) has designed another cell which does not trap bubbles. His cell has one other real advantage—the windows are held in place mechanically rather than by cement. In the other cells described the cement is a problem. Brittle cement yields on temperature change, and plastic cement yields to the prolonged water pressure within, ultimately springing a leak.

Table 1 lists the liquids chosen from a large number because of their high temperature coefficients (Emmons, 1929). They are intended to be used for temperature variation alone and for accuracy, with monochromatic light such as a sodium flame. These liquids are for the most part pure compounds which will not change index on standing or while heated for study on the water cell.

TABLE 1.—*Single variation liquids*

1. Methylene iodide
2. Methylene iodide +
   α–iodonaphthalene
3. α–iodonaphthalene
4. α–iodonaphthalene +
   α–bromonaphthalene
5. o–bromoiodobenzene
6. Phenylisothiocyanate
7. s–Tetrabromoethane
8. Iodobenzene
9. Bromoform
10. 1–2–4 Trichlorobenzene
11. Nitrobenzene
12. Benzonitrile
13. m–Cresyl ethyl ether
14. sec–Butyl benzene
15. Methyl thiocyanate

The refractive index of a liquid depends on both the temperature of the liquid and on the wave length of light used. The change in refractive index of a liquid for 1°C change in temperature is spoken of as the temperature coefficient of the index. The change in refractive index of a liquid with change in wave length of light used is spoken of as the dispersion of the liquid. It is commonly expressed quantitatively in crystallographic literature as the difference in refractive index of the liquid for light of the wave lengths of the F (486mμ) and C (656mμ) Fraunhofer lines, abbreviated to $N_F - N_C$. The dispersion of a liquid as we shall use it covers essentially the same range of refractive index as that covered by the temperature coefficient. For an average index liquid the dispersion may be $N_F - N_C = .020$. By selecting a set of liquids having high dispersion this value may be given a range from .010 for the low indices where dispersion is also low, to .037 for the highest chosen.

Crystals also vary in index with change in wave length though the change is much less than that of liquids. The dispersion of a crystal, like the refractive index, is a characteristic value which may be used for identification. The dispersion of an average crystal may be about .006 to .018. In general the dispersion of both crystals and liquids is higher for those of high refractive index. Among common minerals the dispersion is usually high for those containing iron and titanium. If two or more points are found on a dispersion curve of a crystal then the curve gives by interpolation or extrapolation the indices for any chosen wave length. These values

are the equivalent of an average since the curve is so drawn as to average the determined values. In this way the necessity for making determinations at fixed wave lengths is avoided.

Since liquids have a greater dispersion than crystals, white-light microscope illumination results in a different Becke line for each wave length of visible light, appearing as a rather indefinite spectral band. If on the other hand monochromatic light is used the line becomes sharp and definite, disappearing only when the crystal and liquid agree closely in index. If, further, the wave length of the monochromatic beam is changed, the refractive index of the liquid changes more widely than that of the crystal, giving the liquid a greater spread as in the case of temperature changes. Accordingly, if liquid and crystal are moderately close but do not agree, by changing the wave length, coincidence of indices becomes a possibility. A change toward the shorter wave length (violet) increases the indices, whereas one toward the longer wave length (red) decreases the indices.

Although the change in wave length of light is much more convenient to make than the change in temperature of the mount the temperature change produces a more effective change in refractive index of the liquid. The temperature coefficient of the crystal is negligible, but the dispersion of the crystal being considerable, cancels that much of the effect of the dispersion of the liquid, and must be subtracted from the dispersion of the liquid.

Wherry (1918) and Merwin (Posnjak and Merwin, 1922) employed a valuable new principle which first made accurate results possible through a convenient procedure. By this method mounts are made from two liquids of a set, adjacent in refractive index. Monochromatic light of variable controlled wave length is used for illumination. Coincidence of indices is obtained for different wave lengths in the different liquids. The correct dispersion curve passes through these points. Indices for the desired wave lengths are then read from this curve. If the crystal is biaxial, or if the extraordinary ray of a uniaxial crystal is being studied, care must be taken that the crystal chosen in each mount has exactly the proper orientation.

If temperature and wave-length controls are both used then not only does the liquid acquire a *much* greater index spread than the crystal but a special advantage accrues. By varying the wave length of light used a coincidence of indices of liquid and crystal is obtained, and one point on the dispersion curve of the crystal is plotted. A change in temperature gives the operator the equivalent of a new

mount of a different liquid but the same crystal in the identical orientation. Further change in the wave length gives index agreement of crystal and liquid for a different wave length. Any number of such temperature changes may be made conveniently, followed by changes in the wave length of light, each yielding a new point
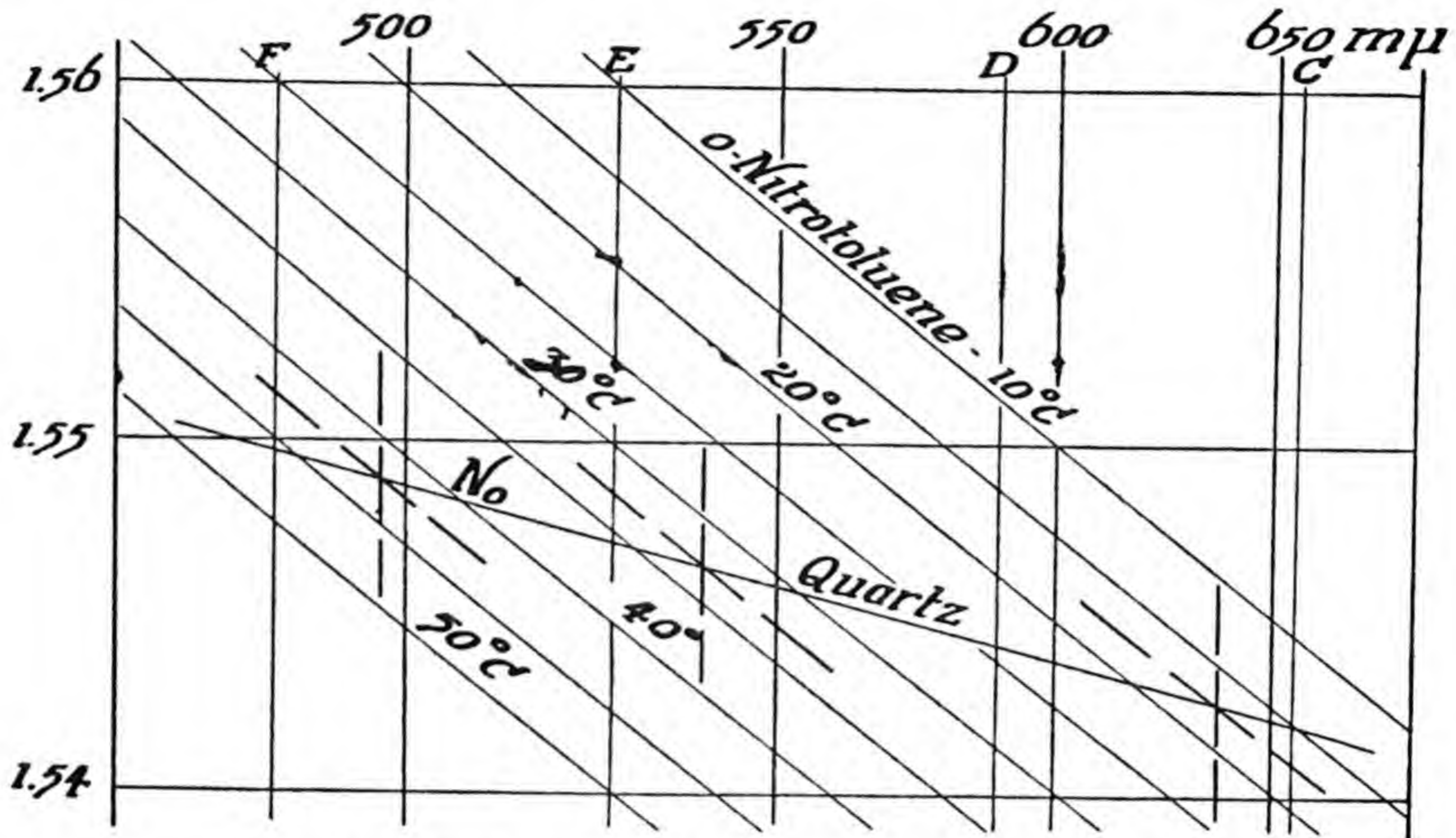
FIGURE 29.—*Principle of double variation method*
Dispersion curve for quartz (ω) is determined in one mount using one liquid and one grain.

on the dispersion curve. By using the same mount in this way we may avoid such errors as that due to a slight difference in orientation in different mounts, or that resulting from choosing grains in different mounts from different parts of a crystal and possibly differing in composition. The advantage of not having to change mounts and search for a suitably oriented grain in each is of course axiomatic. This procedure, which employs variation of temperature and variation of wave length of light is the *double variation procedure*.

Figure 29 illustrates the principle of the method. The ordinate represents refractive indices, the abscissa represents wave lengths of light. The steeply inclined curves are dispersion curves of an immersion liquid, and the gently inclined curve represents the dispersion of the ordinary ray of quartz. This is the curve wanted and unknown. Assume that the temperature of the mount is set at 18°C. By adjusting the wave length and watching the Becke line, the crystal and liquid agree in refractive index at 636mμ— that is, the Becke line disappears at this wave length of light. As-

sume next that the temperature is changed to 33°C. Once more find the wave length at which the Becke line disappears. It will be found to be at 539mu. Again change the temperature and adjust
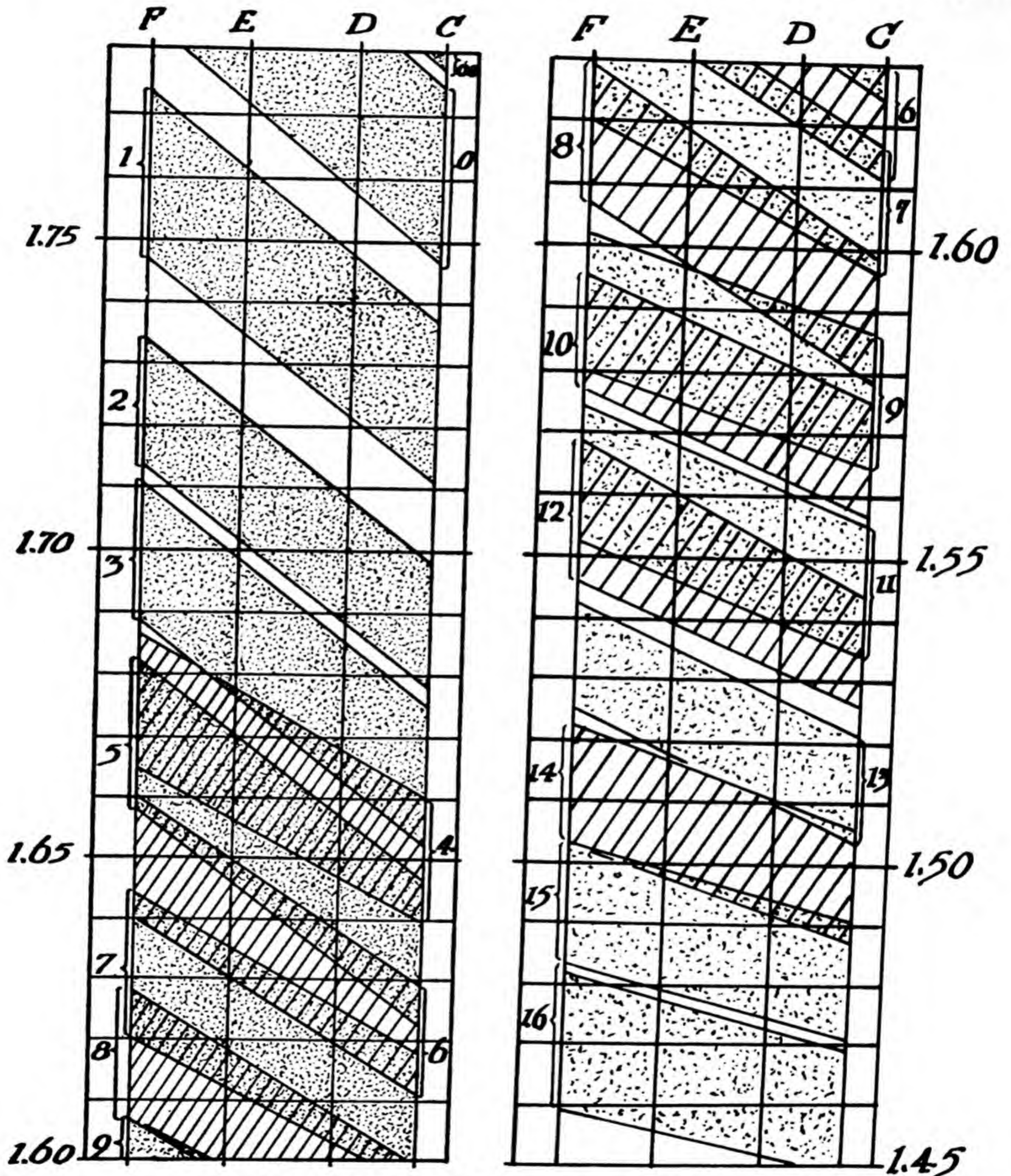
FIGURE 30.—*Double variation liquids*

This set of curves may be used as a guide in selecting a liquid for a mount. Comparatively few liquids cover the entire common index range without gaps.

the wave length. Assume the temperature to be 42°C; the Becke line will disappear at 497mμ. Each of these temperature and wavelength settings is represented by a heavy broken line. Their points

TABLE 2.—*Double variation liquids*

(See Figure 30.)

		B.P. (°C)	$N_C^{10°}$	$N_C^{50°}$	$N_F^{10°}$	$N_F^{50°}$	Δ^{**}	N_F-N_C
00	Ethyl diiodoarsene	....	1.808	1.777	1.834 ($N_{550}^{10°}$*)	1.800 ($N_{550}^{50°}$*)	81	.049 ±
0	Methylene iodide + sulphur	....	1.775 ($N_D^{25°}$)					
1	Methylene iodide	180	1.737	1.711	1.774	1.747	68	.0369
2	α-iodonaphthalene	305	1.698	1.678	1.734	1.714	47	.0368
3	α-iodonaphthalene + α-bromonaphthalene	....	1.675	1.652	1.711	1.689	55	.0365
4	o-bromoiodobenzene	257	1.660	1.640	1.687	1.665	52	.0261
5	Phenylisothiocyanate	220	1.646	1.623	1.682	1.658	58	.0353
6	α-chloronaphthalene	259	1.629	1.611	1.660	1.640	47	.0300
7	Iodobenzene	188	1.618	1.596	1.644	1.620	55	.0247
8	α-naphthyl ethyl ether	276	1.599	1.579	1.628	1.607	50	.0290
9	1,2,3 Tribromopropane	220	1.586	1.565	1.602	1.580	50	.0154
10	m-chlorobromobenzene	196	1.578	1.557	1.595	1.577	47	.0195
11	o-bromotoluene	181	1.555	1.534	1.573	1.552	50	.0181
12	o-nitrotoluene	222	1.544	1.525	1.568	1.547	49	.0228
13	Ethyl salicylate	233	1.521	1.504	1.542	1.525	44	.0203
14	Ethyl benzoate	211	1.505	1.487	1.522	1.503	45	.0164
15	Cymene	176	1.490	1.471	1.503	1.483	49	.0126
16	Methyl thiocyanate	130	1.469	1.449	1.481	1.459	54	.0111

* Wave length in mμ   ** Δ is the temperature coefficient of refraction.

of intersection are the points sought and through which the dispersion curve of the crystal passes.

In actual practice only the dispersion curve (or curves) of the crystal is drawn—it is not necessary to represent the dispersion of the liquid on the graph. The temperature and wave-length settings are established, and the indices are read on a refractometer as will be described. The values are then plotted directly on a dispersion chart.

Table 2 lists the liquids chosen for having high temperature coefficients and high dispersion. These liquids are chosen from a large number of liquids after an extensive search. There are many changes from the set of liquids originally published for this purpose. Especially, bromoform is omitted, and a suitable substitute has been found. Also omitted are o-toluidine and methyl furoate which darken on standing; o-bromoiodobenzene is expensive, but the others are reasonably priced. The list given in Table 2 has no recognized serious limitations as did the original list. Figure 30 expresses the two pertinent optical properties of these liquids graphically and is a guide for choosing a liquid. These liquids are for use when both the temperature of the mount and the wave length of light are to be varied under controlled conditions. Hence we shall speak of them as "double variation liquids."

It will be noticed in Figure 30 that there is an overlap of adjacent liquids made desirable by crystals which fall optically on the border of one of the liquids, where flexibility would otherwise be limited. If the crystal is quite unknown, then four or five preliminary mounts should be made with different liquids chosen from different parts of the most common range of indices—1.50-1.70. A glance at each of these mounts is usually sufficient to indicate about where on the index scale the crystal falls. Then using Figure 30 the proper double variation liquid is chosen, the mount made on the universal stage, the crystal oriented, and the operator is ready to proceed with the determination of all three refractive indices of the crystal grain chosen.

The method recommended for making an immersion mount has been outlined in Chapter 2 as has the procedure for orienting both uniaxial and biaxial crystals. We shall assume therefore that the chosen crystal is mounted in a suitable liquid and oriented on the universal stage. The index of the crystal and liquid may be compared very accurately by the "Becke line" method which under the conditions established functions especially well, because the source of light, being narrow, gives parallel light conducive to the forma-

tion of a good line. The elevation of the mount above the stage of the microscope is also a beneficial factor. In the procedure outlined here one liquid alone is used to determine all three refractive indices of a biaxial crystal. It is required that the liquid have an index range in part between α and γ. A monochromator is preferred as a monochromatic light source.

The operator's time is conserved if he follows a system, usually a procedure of his own if he is experienced. As a suggestion for the beginner the scheme adopted in the writer's laboratory is outlined here. Commonly it is not known which rays are transmitted by an oriented biaxial crystal, unless the necessary steps already outlined have been taken to learn more about the orientation. It is known of course that on removal of the analyzer one critical ray is transmitted, and by rotating 90° on the microscope stage another critical ray is transmitted. For the present the first of these may be known as ray No. 1, and the other as ray No. 2. The third ray, whose critical vibration direction is parallel to the axis of the microscope, is ray No. 3. This ray is read as a "rotation reading" from ray No. 1 or ray No. 2. The procedure then is this: At the chosen temperature, which to start is usually 25° or 30°C., adjust the monochromator to find the wave length at which the crystal and liquid agree in refractive index. Record the ray (No. 1), temperature, wave length, and refractometer reading, preferably on a suitable form such as the data sheet shown at the back of the book. Then rotate 90° on the microscope stage and again adjust the monochromator to find the wave length at which the crystal and liquid agree and record the results as before—this being ray No. 2. Next rotate on the north-south axis (now east-west) as far as convenient but always more than 45° if possible and make the same adjustments and readings on the monochromator and refractometer, recording the results—this is ray No. 3'. Or, instead of rotating on the north-south axis, turn back 90° on the microscope stage and then rotate as far as convenient on the outer east-west axis, at which position read and record the values, also as ray No. 3'. The first of these would be recorded as a rotation reading from ray No. 2, the second as a rotation reading from ray No. 1. In either case record the amount of rotation and the ray from which the rotation was made. As a check, rotations may be made from both ray No. 1 and ray No. 2. These will of course give different index values, but when properly extrapolated to give the true value for ray No. 3 the results should agree. Sometimes the inner stage will strike due north or due east and dip steeply. In such a situation a satisfactory rotation reading

is possible from only one of the rays No. 1 and No. 2. **Bear in mind** that rotation readings must be made by rotating on a horizontal axis *which is perpendicular to the plane of the polarizer.*

Rotations on the north-south axis are never so conveniently made as are those on the outer east-west axis. Accordingly the following procedure will be preferred by the experienced operator to the one recommended above for the beginner, when rotation readings are to be made from *both* rays No. 1 and No. 2 or from ray No. 2 alone toward ray No. 3. After making index determinations on rays No. 1 and No. 2 the microscope stage stands 90° from its zero position—that is, the outer east-west axis is north-south. Bring the microscope stage back to its zero position, make the next rotation toward ray No. 3 (and from ray No. 1) on the outer east-west axis, and return it to its zero position. Next, to make a rotation reading toward ray No. 3 from ray No. 2 rotate 90° on the outer vertical axis. This makes the north-south and outer east-west axes coincident. Then rotate on the outer east-west axis, and the effect is the same as though the rotation were made on the north-south axis. Though the rotation is actually north or south it is to be recorded as east or west according to which direction the rotation was made on the outer vertical axis.

These readings may now be corrected and plotted, but before doing so the temperature is changed, preparatory to making another set of readings. If the readings already made employed light of long wave length (red) then the temperature is to be raised; if the readings employed light of short wave length (blue) then the temperature is to be lowered. Change of 4 or 5 degrees is usually satisfactory. The refractometer requires about 4 or 5 minutes to come to temperature after a change, during which time the corrections may be made and the plotting done.

Sometimes one of the rays may not be reached by wave-length changes at the temperature first used, in which case of course no reading is taken. Successive temperature changes are apt to reach it unless the crystal is one of high birefringence. If only one ray can be reached (No. 1 or No. 2) a rotation reading is made to the other as well as toward ray No. 3. This will be elaborated below.

After having made the corrections and plotted the results of the first set of readings the temperature equilibrium should be established. Another set of readings is then taken and similarly corrected and plotted. In routine work two sets of readings are usually sufficient though more readings lead to greater accuracy.

The points for rays No. 1 and No. 2 establish dispersion curves for these rays. The rotation readings, if all are made at the same rotation, establish another curve, or if rotation readings from both rays No. 1 and No. 2 were made then two curves result. It is not necessary, though it is slightly more convenient, to rotate equally for rotation readings from one ray. If different rotations are made no rotation curve results until all rotation points are corrected and extrapolated to give the true value of ray No. 3.

Hartmann's dispersion net is especially well suited to plotting results. The wave-length scale of this net is not a uniform scale but is adjusted to make the average dispersion curve drawn on it a straight line. Accordingly, for a great many crystals—most of those encountered in daily work—if two points on a dispersion curve are known the entire curve may be drawn in with a straight edge. If several points on a curve are known, then the curve serves more easily to average the points. In representing the results of examples here, the principle of the Hartmann net is used (Figs. 31-38).

A typical case (Table 3; Fig. 31) illustrates the theory just outlined. After the orientation is established (entries I.E-W and N-S), the two vertical symmetry planes were searched for an optic axis. None being found (O.A. 1 and 2) the procedure of Berek and Dodge was followed (entries 2V-1 and 2V-2). The rotation on the outer east-west axis of 54.7° was estimated at 58° but was not corrected. For Dodge's curves (entry 2V-2) Figure 13 was chosen as indicated on Figure 11 by the rotation M—35° under 2V-1. This plate requires that O.V. = 30°. O.E-W was made as large as the setting would permit (60°) and corrected (to 55.5°). 2V is 47°. Although this figure may be obtained from the refractive indices to be determined, a comparison of the two values of 2V gives a check on the results. Accordingly, if it is convenient, it is a good practice always to read the optic angle, either directly or by the Berek or Dodge method, along with a determination of the refractive indices.

Return the crystal to the oriented position to measure the indices. From a brief examination of two or three preliminary mounts the general index has been learned, and a double variation liquid selected from Figure 30. From Figure 30 it is known that a high temperature is needed, and 45° is chosen. The first five entries are made for ray No. 1, the microscope stage is rotated 90°, and the first five entries made for ray No. 2. Next the microscope stage is returned to its zero position, and the outer east-west axis is rotated 56° S and a reading made. Since this is a rotation from the vibration of ray No. 1, it is so recorded (entries 1-5, 8, 9). Similarly the outer

vertical axis is rotated 90°, bringing in ray No. 2, and the outer east-west axis is rotated again, 50° S. Since the outer vertical axis was turned clockwise, this south rotation is the equivalent of a rotation to the east and is so recorded.
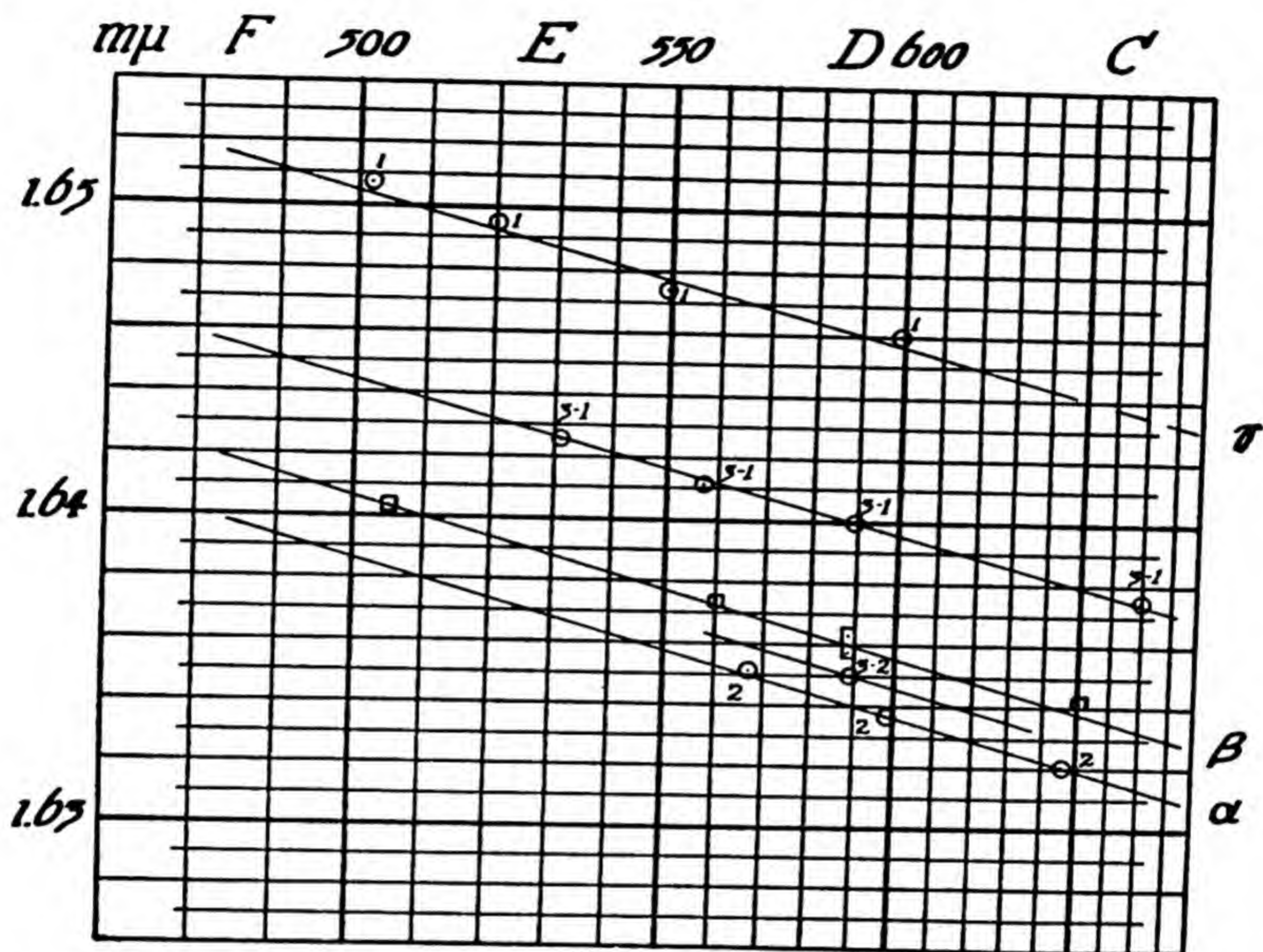
FIGURE 31.—*Hartmann net graph of barite crystal recorded in Table 3*
Typical double-variation work sheet by which all indices of a crystal are determined in one mount.

At this point the temperature is changed, and while the instruments are equalizing entries in columns 6 and 7 are made, and the points are plotted on the dispersion net. The values for column 6 are obtained from a curve similar to Figure 41, provided with the refractometer by the manufacturer. The plotted points on the dispersion net guide the operator in making further temperature changes.

The extrapolations of ray No. 3' (columns 10-13) may be done now or later as time permits. There is no advantage in doing them as the work progresses; they are not needed as a guide to further readings as are the observed readings. The technique of extrapolation will be discussed directly.

When the current plotting is done two readings may be taken on the refractometer a few seconds apart to be sure temperature equilibrium is established; then the next set of readings and recordings may be made—in this case lines 5, 6, and 7. After plotting the second set

TABLE 3.—*Double variation data*

(Fig. 31)

MINERAL LABORATORY

Mineral. Barite (# 8880) ....Locality..

I. E–W	0°	
N–S	11° W	
O. A. 1	— —	
2	— —	
	2V–1	2V–2
O. V.	〔45°	〔30°
O. E–W	58° N	60° N
M	〔35°	〔39°
2V	45–50°	47°

Orientation: α	E
β	⊥
γ	N
I. V.	
Immersion Liquid	4
Hemispheres	1.559
Zero Values: Mic	0°
O. V	89.5°

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor·	Ray #3
1	46	44	520	1.6390	.0105	1.6495						
2	"	"	598	1.6348	−.0011	1.6337						
3'	"	"	557	1.6368	.0043	1.6411	56° S	1	.0061	560	−.0037	1.6374
3'	"	"	589	....	....	1.6350	50° E	2	.0009	589	.0008	1.6358
1	37	36	549	1.6418	.0055	1.6473						
3'	"	"	589	....	....	1.6400	56° S	1	.0061	589	−.0037	1.6363
2	"	"	645	1.6380	−.0060	1.6320						
2	53	51+	567	1.6321	.0030	1.6351						
1	"	"	502	1.6368	.0140	1.6508						
3'	"	"	531	1.6341	.0084	1.6425	56° S	1	.0060	505	−.0037	1.6403
3'	20.5	21	670	1.6457	−.0082	1.6375	56° S	1	.0061	650	−.0037	1.6341
1	"	"	599	1.6473	−.0013	1.6460						

of readings a survey may be made to learn how many more points are needed. Usually it is well to compile adequate points to fix one curve slope well; the others ordinarily fit into this picture. It is obvious that another point toward the red end of the curve of

ray No. 1 would fix this curve reliably. Accordingly, while taking the third set of readings at 50+°C the fourth temperature setting around 20°C is contemplated. This completes the recordings for the crystal.

We now have three curves (or four if check rotation readings were made from both rays No. 1 and No. 2) : the true dispersion curve of ray No. 1, the curve of ray No. 2, and the curves for rotation readings toward ray No. 3. Since the rotation is almost invariably less than 90° the value for the rotation reading is to be corrected and extrapolated to obtain the value for a 90° crystallographic rotation; in other words the true dispersion curve of ray No. 3 is to be obtained.

Assume that the rotation was made from ray No. 1. Then there is known the index of the ray from which we have rotated, the index at the chosen rotation, and the amount of rotation. The rotation as read on the instrument is to be corrected as outlined in Chapter 4 except that, instead of using the mean index of the mineral, the real index of the transmitted ray is used in each setting of the stage. (In several of the following examples the hemispheres were chosen to increase the corrections for illustrative purposes.) Before making the extrapolation, the dispersion curves of the three (or four) rays measured must be drawn, because the extrapolation is made for one or more definite wave lengths of light, which are rarely those of measured points on two curves. Accordingly, for the assumed rotation from ray No. 1 to No. 3, choose any wave length, usually that of one of the Fraunhofer lines, determine on the Hartmann net and record in the table the index difference between the curves. This is the index change produced by the true crystallographic rotation. The figure in column 12 is not added to the figure in column 7 unless the two wave-length readings are the same (columns 4 and 11). Even then the figure of column 7 may not be used unless it lies on the constructed curve.

By means of the equation of the ellipse, the difference between the measured index No. 3' and the desired index of ray No. 3 may be determined. To simplify this calculation a diagram is provided (Pl. 10 a, b). If the index change on rotation from ray No. 1 to ray No. 3' is a decrease, find this decrease on the ordinate scale; if the index change is an increase find the value on the abscissa. In the first case follow to the right along a horizontal line from the ordinate value, in the second case follow vertically up from the abscissa value. Determine the point of intersection of the line followed, with the radially inclined line which represents the corrected rotation.

Each radial carries two designations—one for an index increase ("abscissa scale") and the other for an index decrease ("ordinate scale"). From the point of intersection thus found either (1) follow one of the parallel lines, which are inclined down to the right and up to the left, to either end. The value indicated by this line is the difference in index between ray No. 1 and ray No. 3. Or (2) follow from the original point of intersection perpendicularly to the other co-ordinate scale. The value so indicated is the amount to be subtracted from (or added to) ray No. 3′ to obtain ray No. 3 at the wave length chosen. This should be done for more than one wave length of light since the dispersion curves are not necessarily parallel. Plot the points so found and through them draw the dispersion curve of ray No. 3. The reference numbers 1, 2, and 3 may now be discontinued and the curves properly named α, β, and γ.

Let us now complete the discussion of Table 3 and Figure 31. Choosing wave length 560 measure on the Hartmann net the index difference between ray No. 1 and No. 3′; it is .0061. Enter these in columns 10 and 11. Since ray No. 1 is higher in index than Ray No. 3′ the rotation causes an index decrease. On Plate 10a find the value .0061 on the ordinate and follow horizontally to the 52° (corrected from 56°) radial for the ordinate scale. From this point follow vertically down to the abscissa where the value is .0037. This amount is subtracted from the index of ray No. 3′ to give ray No. 3. Enter the value .0037 with the proper sign in column 12 headed additive correction, and the sum of the refractive index as read from the curve at wave length 560 and column 12 in column 13. This may then be added to the net. It is to be noted that there is no calculation, and the time needed for the extrapolation is negligible. (2V calculated from the curves of Figure 31 on Plate 11 agrees well with the indirect determination of Table 3.)

Plate 10 is divided into parts (a) and (b). Part (a) is that mainly used since it concerns crystals of low and medium birefringence; it is the enlarged lower left-hand corner of part (b). Commonly the lower left-hand corner of part (a) is used on minerals of the birefringence of feldspar. It is within the limits of accuracy of reading the chart, and within the limits of accuracy of the data, to use the ordinate and abscissa values of .01 and .02 as .001 and .002, and it is much more convenient. These values are therefore included in parentheses. The graphic key to the use of both parts (a) and (b) is given on part (b).

Part (b) is for use with crystals of high birefringence only. The higher part is at present of theoretical interest mainly but not entirely, and less so as methods are being found to study such difficult

substances in a practical way. (*See* Chapter 10.) Part (b) shows strongly the curvature of the radial lines; it also requires some real corrections to be made for high birefringence and high index that are wholly negligible on part (a). For determination of a crystal only, even these corrections may usually be neglected since the number of crystals known in the high index and high birefringence field are comparatively few, and no confusion will result. But the corrections must be taken into account if the optical constants of these crystals are to be accurate. The method adopted for them is simpler than that originally published. It may be explained by an example.

Assume that a corrected rotation of 45° from a ray having an index of 2.2 produces an index increase of .100. On the abscissa scale of the main chart (Pl. 10b) find the value .100, follow vertically to the intersection with the radial 45° (for the abscissa scale), and note the value of the total birefringence for the two rays concerned as indicated by the lines inclined down to the right. This is .225. On the "abscissa correction" chart find the abscissa value 45°, follow vertically to the birefringence value .225, follow horizontally to the left to the intersection with the index line for 2.2 and then down to the correction scale. It is +1.3°. Add this to the value 45° and repeat the procedure on the main chart using 46.3° instead of 45°. The total birefringence is .213 instead of .225 (*Note* that the difference, .012, is not enough to cause serious confusion if the result were to be used only for the determination of an unknown.)

Knowing the three critical refractive indices, simple subtraction gives the birefringence γ—α or the partial birefringences γ—β or β—α. Wright has provided a convenient graphical solution of the relationship between the total birefringence, the partial birefringence, and the optic angle (Pl. 11). Its use is simple—the abscissa is γ—α, the ordinate is γ—β or β—α. The point of intersection of these values lies on an inclined line which indicates 2V. If the smaller of the partial birefringences is chosen the optic angle indicated is that about the acute bisectrix. If the optic angle and any two refractive indices are known (and therefore the total or partial birefringence) the third refractive index may be learned from the chart.

The double variation procedure offers other advantages. Although many crystals have a birefringence so low that all three indices lie within the double variation range of a chosen liquid, others do not. The possibilities are many, but a few illustrations will demonstrate how these crystals may be studied without making several mounts. The crystal index range and the liquid index range must overlap a reasonable amount, enough to give the slope of two dispersion curves

of the crystal, not necessarily the curves of the critical rays α, β, and γ, but any one of these and ray No. 3′, or No. 3′ and No. 3″. The farther apart these curves are, rotationally speaking, the greater the accuracy, of course. From one mount (one liquid) all three refractive indices of a crystal may be determined even though none of them actually lie within the range of the liquid itself. Specifically the cases are these or their equivalents:

(1) In a uniaxial crystal, if we know ε or ω and ε′ by means of Plate 10 we can determine the other critical index.

(2) In a uniaxial crystal, if the liquid index range does not include either ε or ω but lies wholly between them, we can determine two dispersion curves, ε′ and ε″, at known rotations from either ε or ω and by means of Plate 10 determine both ε and ω. This is done by finding two points on one of the parallel inclined lines, each point (1) lying at the intersection of a radial which indicates the rotation measured (and corrected) from the cardinal orientation chosen, and (2) marking one limit of a vertical or horizontal intercept (according to whether the rotation produced an index increase or index decrease) equal to the difference in index for one wave length of light between the two curves. (*See* Figure 33.) Practically, this is most easily done as follows: Determine the difference in index for one chosen wave length between the two index curves, find the inclined parallel line which represents this value, and lay a paper along this line marking its end points on the paper. Then, keeping the edge of the paper parallel to the parallel inclined lines, move it radially outward, placing one end point mark on one of the radials representing one of the dispersion curves, until the other end point meets the other radial which represents the other dispersion curve. In this position the inclined line at the edge of the paper represents the total birefringence; the ordinates and abscissae of the end points on the paper are the amounts to be added to and subtracted from the respective indices to obtain ω and ε. Beginners may be in doubt in selecting the index to which the indicated values are to be added or subtracted, suggesting the need for further explanation. Suppose two rotations 30° and 60° from an oriented position at which no readings can be made yield an index increase. Then the points are located as described on the 30° and 60° radials. Consider the lower right-hand point (on the 60° radial); the ordinate value of the point is to be added to, and the abscissa value is to be subtracted from, the upper dispersion curve to give ε and ω. Similarly the ordinate value of the upper left-hand point (30° radial), is to be added to and the abscissa value is to be subtracted from the lower dispersion curve, which is the 30° rotation reading, to

obtain ε and ω. Both will give the same result; therefore only one is done.

Figure 32 shows in solid lines the determined dispersion curves of a tourmaline crystal (ε' and ε"). From these curves the true values of
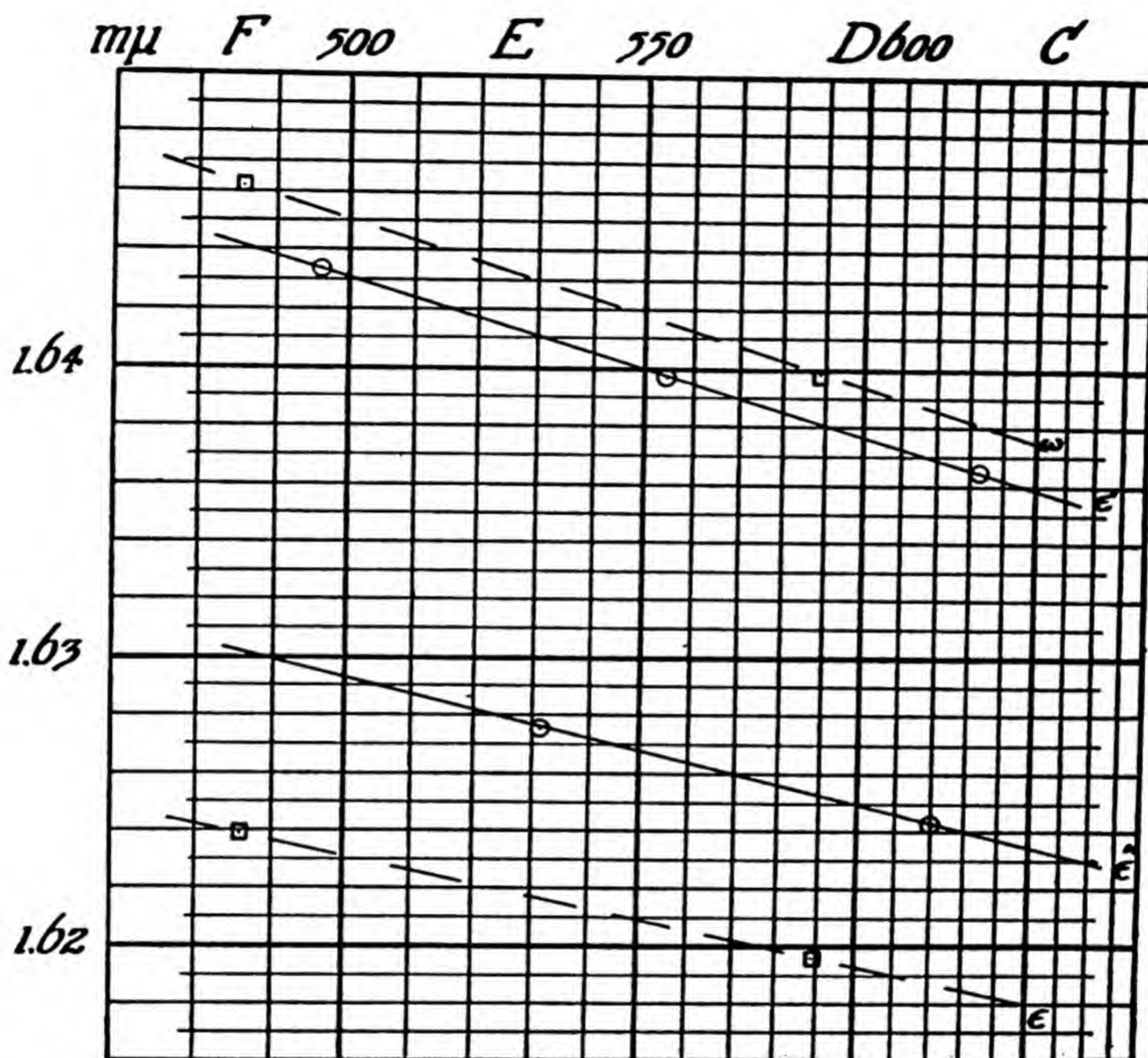
FIGURE 32.—*Hartmann net graph of dispersion curves of tourmaline crystal recorded in Table 4*

From two intermediate readings (3' and 3") the critical indices ε and ω are learned (Fig. 33).

ε and ω (the broken lines) are to be obtained by extrapolation. From the data on orientation (Table 4) it is learned that the optic axis is vertical when the inner stage is inclined 23.5° N. In this orientation the ordinary ray is transmitted, but the value of the ordinary ray is not yet known. The inclination of the inner stage (23.5°) is however to be corrected for the difference in index between the crystal and the hemispheres. Two procedures are open: (1) The value of the ordinary ray may be estimated with suitable accuracy since high accuracy for this purpose is not necessary except for steep inclinations; (2) a hurried preliminary determination of the ordinary ray may be made by following through the extrapolation without corrections and then re-

TABLE 4.—*Double variation data*

(Fig. 32)

MINERAL LABORATORY

Mineral. Tourmaline ....Locality...

I. E–W	— —		Orientation: α	
N–S	— —		β	
O. A. 1	23.5° N		γ	
2			I. V.	
	2V–1	2V–2	Immersion Liquid	6
O. V.	(	(	Hemispheres	1.516
O. E–W			Zero Values: Mic	36°
M	(	(	O. V.	90°
2V				

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray #3
E′	31	31 –	496	1.6280	.0153	1.6433	5° N	0. E–W				
E″	43	42	620	1.6277	– .0035	1.6242	40° S	″				
E″	52+	51	531	1.6193	.0083	1.6276	″	″				
E′	23	23	554	1.6350	.0047	1.6397	5° N	″				
E′	17	17	632	1.6411	– .0047	1.6364	″	″				

peating the extrapolation using this approximate value of ω for the corrections. Using 1.640 as the value of ω for the D line, 23.5° is corrected on Plate 8 to 21.5°. Similarly 5°N, the orientation in which the first rotation reading is made (ε′), is corrected to 4.5°N, and 40°S is corrected to 36°S as the orientation for ε″. For both ε′ and ε″ the actual values as read from the determined curves are used in making corrections. In this illustration the hemispheres $N_D = 1.649$ would ordinarily be used; $N_D = 1.516$ was used instead to make the corrections large for illustrative purposes. The actual rotations used on Plate 10 for the extrapolation are ε′ 17° (21.5° — 4.5°), and ε″ 57.5° (21.5 + 36°).

Figure 33 shows the principle of using the plate for this purpose. The index difference for the D line between the curves ϵ' and ϵ'' is .0128. Find this value on both ordinate and abscissa and mark the points on the edge of a sheet of paper. Since the rotations produced
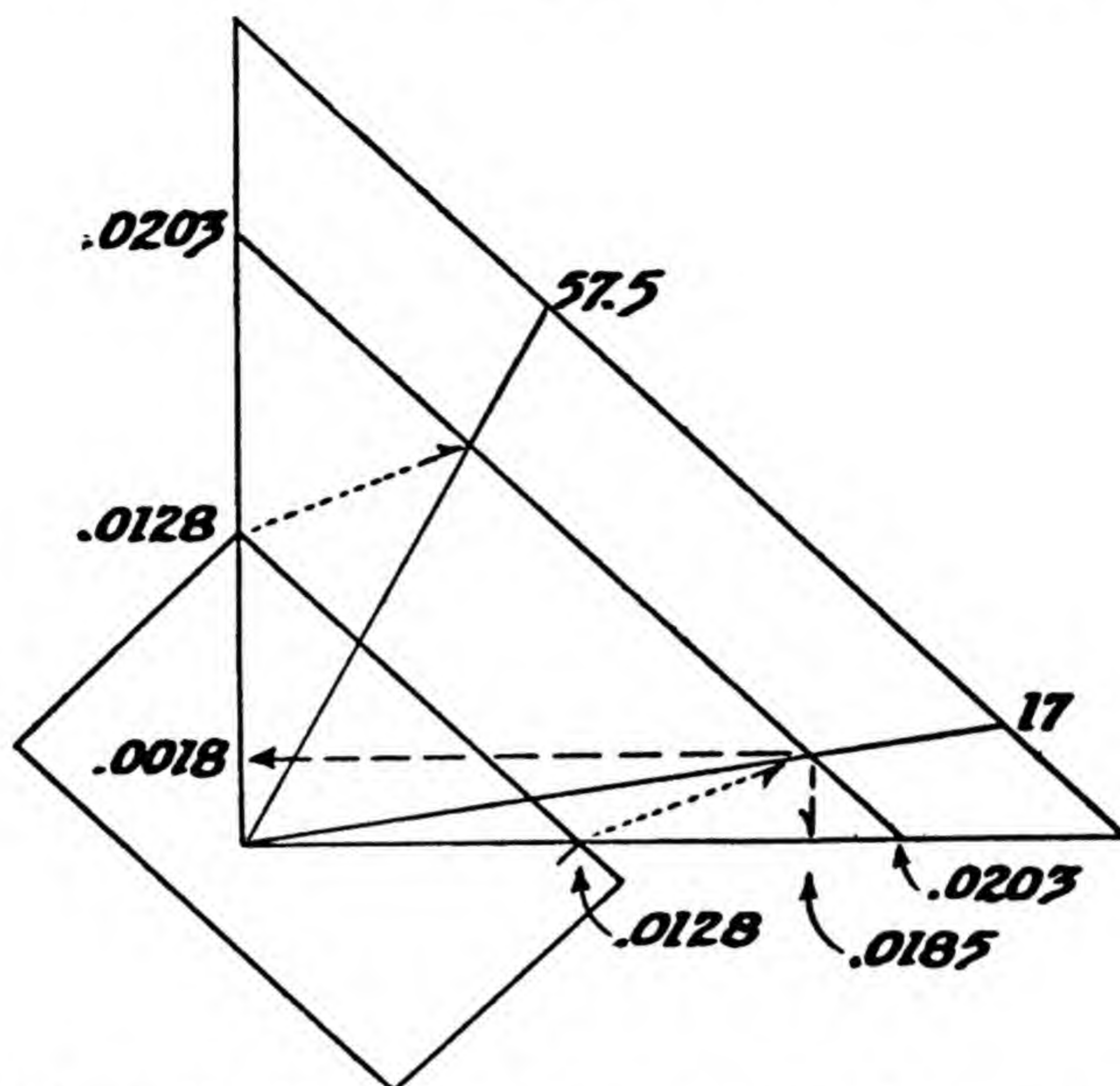
FIGURE 33.—*Method of using refractive index variation diagram (Pl. 10)*

For data of Table 4 and Figure 82 to extrapolate to the indices
ϵ and ω from the intermediate values ϵ' and ϵ''.

an index decrease, this gives the *vertical* intercept required. Keeping the sheet of paper oriented, move it until the indicated points fall on the proper ordinate radials 17° and 57.5° as shown by the dotted lines. Choosing the radial 17°, the ordinate and abscissa values read are .0018 and .0185. Add .0018 to and subtract 0.185 from 1.6381 to get 1.6399, ω_D and 1.6196 ϵ_D. Proceed similarly for other wave lengths. These data are plotted in Figure 32.

(3) In a biaxial crystal it is ordinarily possible to measure rays No. 1 and No. 2 directly, but seldom possible to rotate adequately to get ray No. 3. This case has already been illustrated in Figure 31. The identical procedure is used if ray No. 3 lies beyond the range of the liquid.

(4) In a biaxial crystal, β (as ray No. 1 or No. 2) may be available to direct measurement, but the other transmitted ray may be too

high or too low (γ or α). There are two possible procedures, the first being preferred as it affords a check by means of the optic angle. It is: (1) Suppose ray No. 1 is β. Then three readings will be made for each temperature used. One will be on ray No. 1 (β), one will be a rotation to ray No. 3′ from ray No. 2, and the third will be a rotation to ray No. 3″ from ray No. 2. The rotations for No. 3′ and 3″ will be chosen as far apart as the liquid conveniently permits. The optic angle should also be determined. From the curves No. 3′ and No. 3″ the true values for α and γ are learned, and β is read directly. The value of 2V is calculated from these by means of Wright's diagram and compared as a check with the value as read directly (Fig. 34; Table 5).

In Figure 34 the curves β, No. 3′, and No. 3″ from No. 2 are indicated. α and γ are determined as were ε and ω in paragraph (2) above. For this purpose some of the pertinent data are as follows. The rotation 10° for No. 3′ is corrected to 9.7°, and the rotation 40° for No. 3″ is corrected to 39.2°. Selecting the wave length 600mμ, No 3′ is 1.6834, and No. 3″ is 1.6712. The difference is .0122. These three figures—9.7°, 39.2°, and .0122—are used on Plate 10a as others were in Figure 33 to learn the value $\gamma - \alpha = .0323$. The ordinate and abscissa values for the radial 39.2 at the birefringence value .0323 are read as .0192 and .0131. To No. 3″ at 600mμ given above as 1.6712 add .0131 and from it subtract .0192 to learn γ and α. $\gamma = 1.6843$; $\alpha = 1.6520$. Plot these on the figure, do the same for 500mμ or any other convenient wave length, and draw the γ and α curves. $\beta - \alpha$ at 600mμ is read on the net as .0156. Use this value and $\gamma - \alpha = .0323$ on Plate 11 to learn 2V. It is 88°. In Table 5 the entry O.A.1. = 47°E when corrected for index difference between crystal and hemispheres agrees well with this figure; it is 89°.

The second procedure is (2) suppose ray No. 1 is β and that the inclination of the stage makes impossible or undesirable rotations of suitable proportions from ray No. 2. Rotate from ray No. 1 to ray No. 3′ and extrapolate to ray No. 3. Measure 2V and calculate ray No. 2 with the aid of Plate 11 (Fig. 35; Table 6).

If α (or γ) as ray No. 1 or No. 2 of a biaxial crystal is available to direct measurement in the chosen liquid, but neither of the other two critical rays is, all three indices may still be learned without making another mount. Rotate from α toward ray No. 3 (β or γ) and determine a dispersion curve for ray No. 3′. This will give ray No. 3. Determine 2V either by direct measurement or by the method of Berek or Dodge. Then using Wright's diagram, as already outlined, ray No. 2 may be learned (Fig. 36; Table 7).
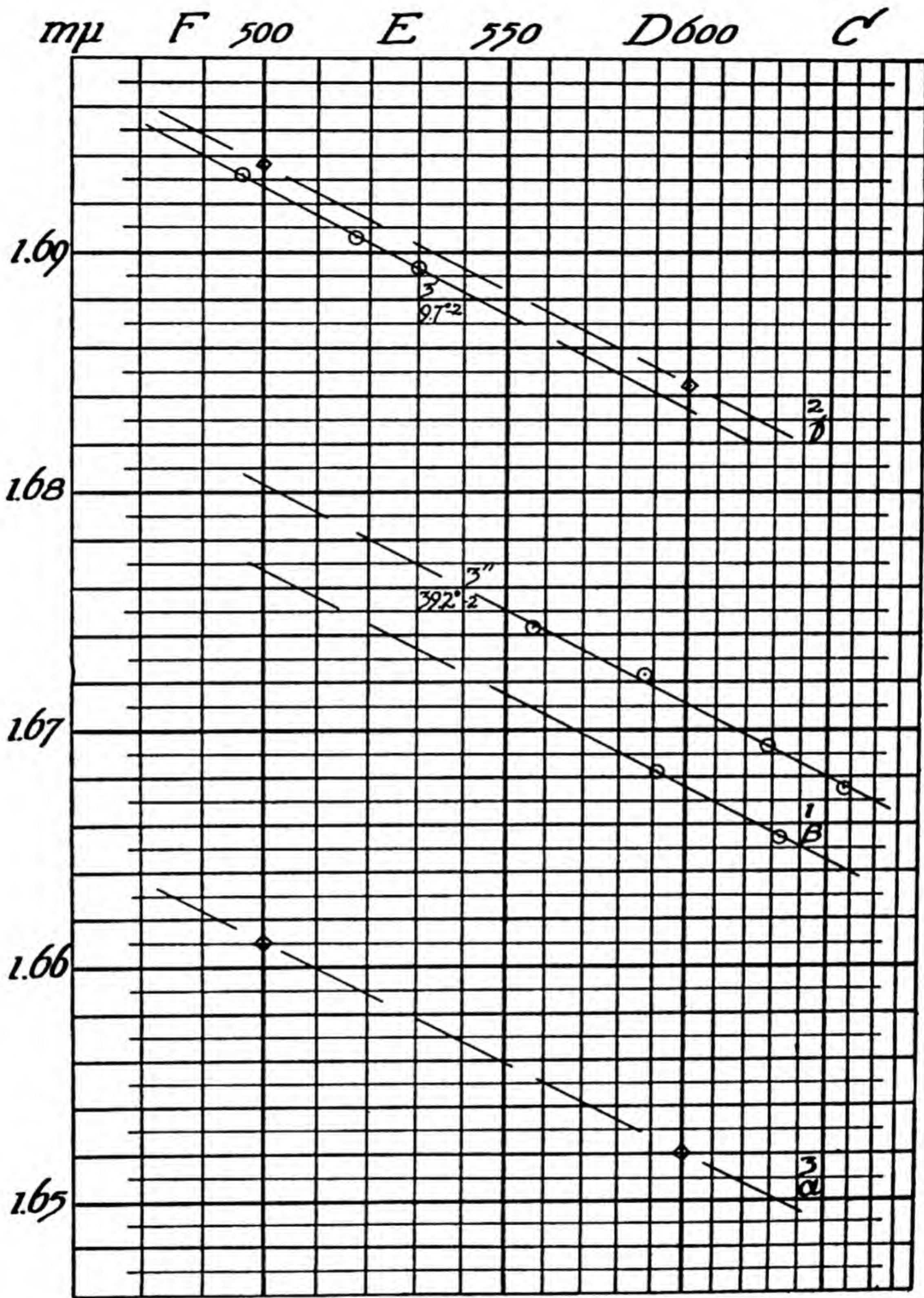
FIGURE 34.—*Determination of dispersion curves of an olivine crystal*
(*Table 5*)
With the aid of Plate 10, reading β directly and extrapolating
to α and γ.

(5) Suppose the liquid index range includes neither α, β, nor γ but
lies either between α and β or between β and γ. Following the method
outlined in case 2 determine two of the rays by extrapolation on Plate
10 from dispersion curves 3′ and 3″. Determine 2V and using the
method outlined in case 4 determine the third ray (Fig. 37; Table 8).

TABLE 5.—*Double variation data*

(Fig. 34)

MINERAL LABORATORY

Mineral.......Olivine...Locality.........................

I. E–W	14.5° N
N–S	13.5° W
O. A. 1	47° E
2	

	2V–1	2V–2
O. V.	(	(
O. E–W		
M	(	(
2V	(+) 88°	

Orientation: α	⊥
β	N
γ	E
I. V.	
Immersion Liquid	3
Hemispheres	1.649
Zero Values: Mic	0°
O. V	90°

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray #3
3′	24	24	517	1.6784	.0122	1.6906	10° E	2				
3″	"	"	628	1.6740	–.0047	1.6693	40° E	2	.0122	600	.0131	1.6843
3″	31+	31+	588	1.6720	.0003	1.6723	"	"				
3′	"	"	496	1.6760	.0172	1.6932	10′ E	2				
1	"	"	632	1.6707	–.0052	1.6655						
1	40–	39–	591	1.6684	–.0002	1.6682						
3″	"	"	557	1.6694	.0048	1.6742	40° E	2				
3″	19–	19+	657	1.6752	–.0077	1.6675	"	"				
3′	"	"	530	1.6798	.0095	1.6893	10° E	"				

In Figure 37 are given two solid line curves. One is No. 3′ which represents a rotation reading at 20° (uncorrected) from ray No. 2, and the other No. 3″ which represents a rotation reading at 45° from ray No. 2. As before, these are to be corrected and become 19.5° and 44.5°. The difference is .0136 at wave length 600mμ as read on the net. These three figures, used on Plate 10, indicate a birefringence
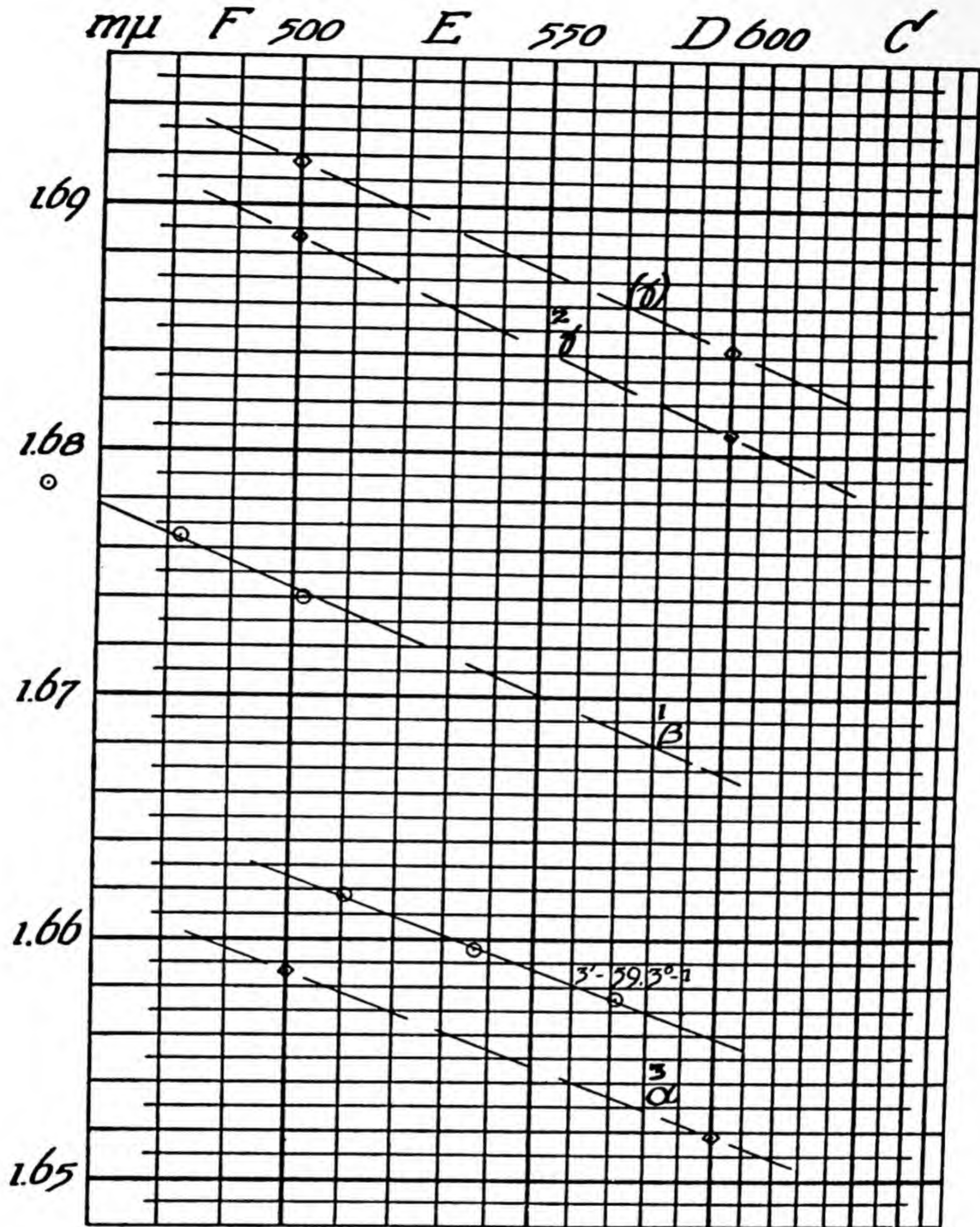
FIGURE 35.—*Determination of the dispersion curves of an olivine crystal (Table 6)*

With the aid of Plates 10 and 11. Reading β directly, extrapolating to α on Plate 10 and calculating γ on Plate 11 from $2V$ and β–α. This gives γ–α which is added to α to obtain γ. The upper and incorrect γ curve is quite easily obtained from the incautious use of Plate 11.

of .0347. The co-ordinate values at the 44.5° intersection with this birefringence are $+$.0173 and $-$.0174. These added to 1.6682, which is the index at 600mμ for ray No. 3″, give $\alpha = 1.6508$ and $\gamma = 1.6855$. β is to be determined by means of the observed value of V and Wright's diagram (Pl. 11). The data are $\gamma - \alpha = .0347$, $V = 43.5°$ after correction. Using these data on Plate 11, $\beta - \alpha$ is

TABLE 6.—*Double variation data*

(Fig. 35)

MINERAL LABORATORY

Mineral................Olivine..Locality...

I. E–W	28° S		Orientation: α	⊥
N–S	5.5° W		β	N
O. A. 1	44° E		γ	E
2			I. V.	
	2V–1	2V–2	Immersion Liquid	5
O. V.	(	(	Hemispheres	1.649
O. E–W			Zero Values: Mic	359.5°
M	(	(	O. V	90°
2V				

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray #3
1	22–	22+	482	1.6561	.0205	1.6766						
3'	''	''	537	1.6515	.0081	1.6596	60° N	1	.0119	500	–.0040	1.6585
3'	13–	14+	571	1.6548	.0028	1.6576	''	''	.0110	600	.0037	1.6519
1	''	''	502–	1.6585	.0155	1.6740						
1	31	31	464–	1.6527	.0257	1.6784						
3'	''	''	510+	1.6482	.0136	1.6618	''	''				

.0165, and β is 1.6673. Similar data may be found for the wave length 500mμ.

In this example the rotation readings are between α and γ. In a crystal of high birefringence such a condition means a large index change on rotation. This, then, is a most unfavorable condition for the application of this technique. A better condition is that in which the rotation is made between γ and β or β and α, which is more likely to permit a rotation greater than 45°.

Other possibilities are variations of these five. We may now recall a statement made earlier that by means of the double variation method, employing the universal stage, all three refractive indices
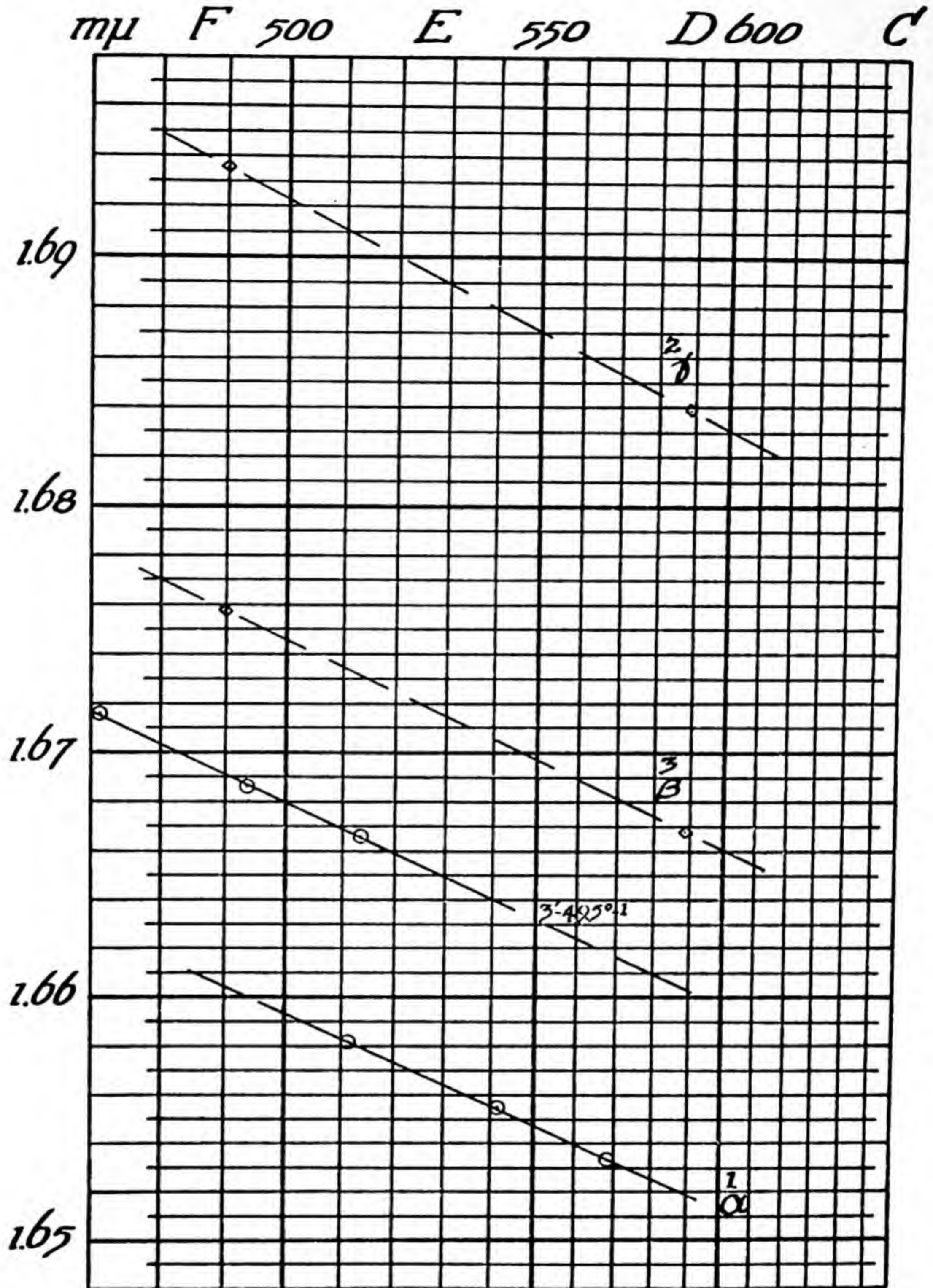
FIGURE 36.—*Determination of the dispersion curves of an olivine crystal (Table 7)*

With the aid of Plates 10 and 11. a and ray 3′ are read on the stage, and 2V is determined by the method of Dodge. Ray 3 (β) is determined by extrapolation on Plate 10. This gives β–a. This value and 2V used on Plate 11 give γ–a which added to a gives γ.

of a biaxial crystal may be determined in one liquid mount only, regardless of the birefringence of the crystal provided only that the liquid range makes it possible to measure two dispersion curves of the crystal whether these curves are a, β, or γ or intermediate values. The higher the birefringence and the greater the extrapolation the less the accuracy, of course.

TABLE 7.—*Double variation data*

(Fig. 36)

MINERAL LABORATORY

Mineral. Olivine ....Locality......................................

I. E–W	20.5° S		Orientation: α	N
N–S	42.5° W		β	⊥
O. A. 1	— —		γ	E
2	— —		I. V.	
	2V–1	2V–2	Immersion Liquid	5.
O. V.	(	⎛ 45°	Hemispheres	1.649
O. E–W		70° N	Zero Values: Mic	0°
M	(	⎛ 48°	O. V	90°
2V		+86°(+)		Ray # 1 = α

Ray	T. 1	T. 2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray # 3
1	19.5	20.5	568	1.6502	.0032	1.6534						
3'	"	"	513	1.6535	.0130	1.6665	50° N	1				
3'	28.5	28.5	493	1.6508	.0177	1.6685	"	"				
1	"	"	541+	1.6484	.0072	1.6556						
1	38–	37–	511	1.6447	.0135	1.6582						
3'	"	"	471	1.6480	.0234	1.6714	50° N	1				
									.0085	589	.0065	1.6603
									.0087	490	.0067	1.6691
				β – a =	.0150 (λ	589) 2V	=86 γ	– a =	.0320			
				β – a =	.0154 (λ	490)	" "	=	.0330			

One more advantage which is merely one of the cases cited above is the ability to determine by this method of extrapolation refractive indices which lie entirely above the range of standard liquids. For instance, if ε and ε′ (or ε′ and ε″) for such a crystal as siderite or smithsonite are determined by immersion in one of the higher liquids (or
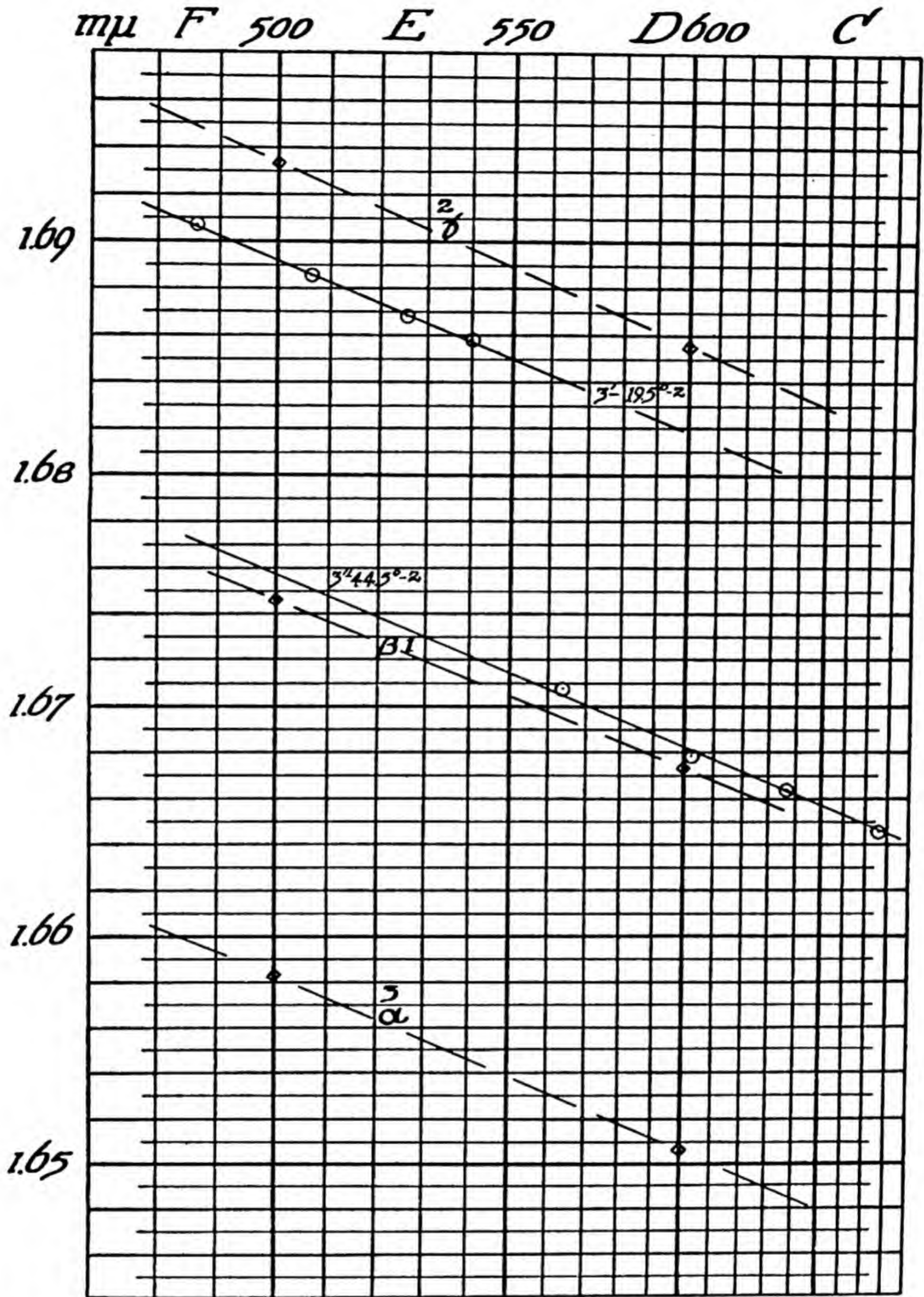
FIGURE 87.—*Determination of dispersion curves of an olivine crystal*
(*Table 8*)

With the aid of Plates 10 and 11. Rays 3′ and 3″ are determined on the instrument, and V is read directly. From 3′ and 3″ (from 2) with the aid of Plate 10 rays 2 (γ) and 3 (α) are determined. This gives γ–α which applied on Plate 11 with V gives γ–β from which β is obtained.

better in two liquids for a crystal of such high birefringence) ω may be learned from these values on Plate 10 even though ω is in the neighborhood of 1.90 (Fig. 38; Table 9). The extrapolation here is wide,

TABLE 8.—*Double variation data*

(Fig. 37)

MINERAL LABORATORY

Mineral. . . . . .Olivine. . . . . .Locality . . . .

I. E–W	3° S		Orientation: α	⊥
N–S	17° E		β	N
O. A. 1	47° W		γ	E
2			I. V.	
	2V–1	2V–2	Immersion Liquid	3
O. V.	(	(	Hemispheres	1.649
O. E–W			Zero Values: Mic	0°
M	(	(	O. V	90°
2V	87+°			

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray #3
3′	27	27	525	1.6763	.0105	1.6868	20° W	2				
3″	"	"	636	1.6720	−.0057	1.6663	45° W	2				
3″	35+	34	602	1.6696	−.0017	1.6679	"	2				
3′	"	"	506	1.6740	.0145	1.6885	20° W	2				
3′	43	42	486	1.6712	.0194	1.6906	"	2				
3″	"	"	564+	1.6671	.0037	1.6708	45° W	2				
3″	20	21	677	1.6739	−.0094	1.6645	"	2				
3′	"	"	540	1.6782	.0076	1.6858	20° W	2				
									.0136	600	.0347	
										600	.0173	1.6855
										600	.0174	1.6508
			600	γ − α	= .0347	V = 43	.5	β −	a = .01	65	β = 1.6	673
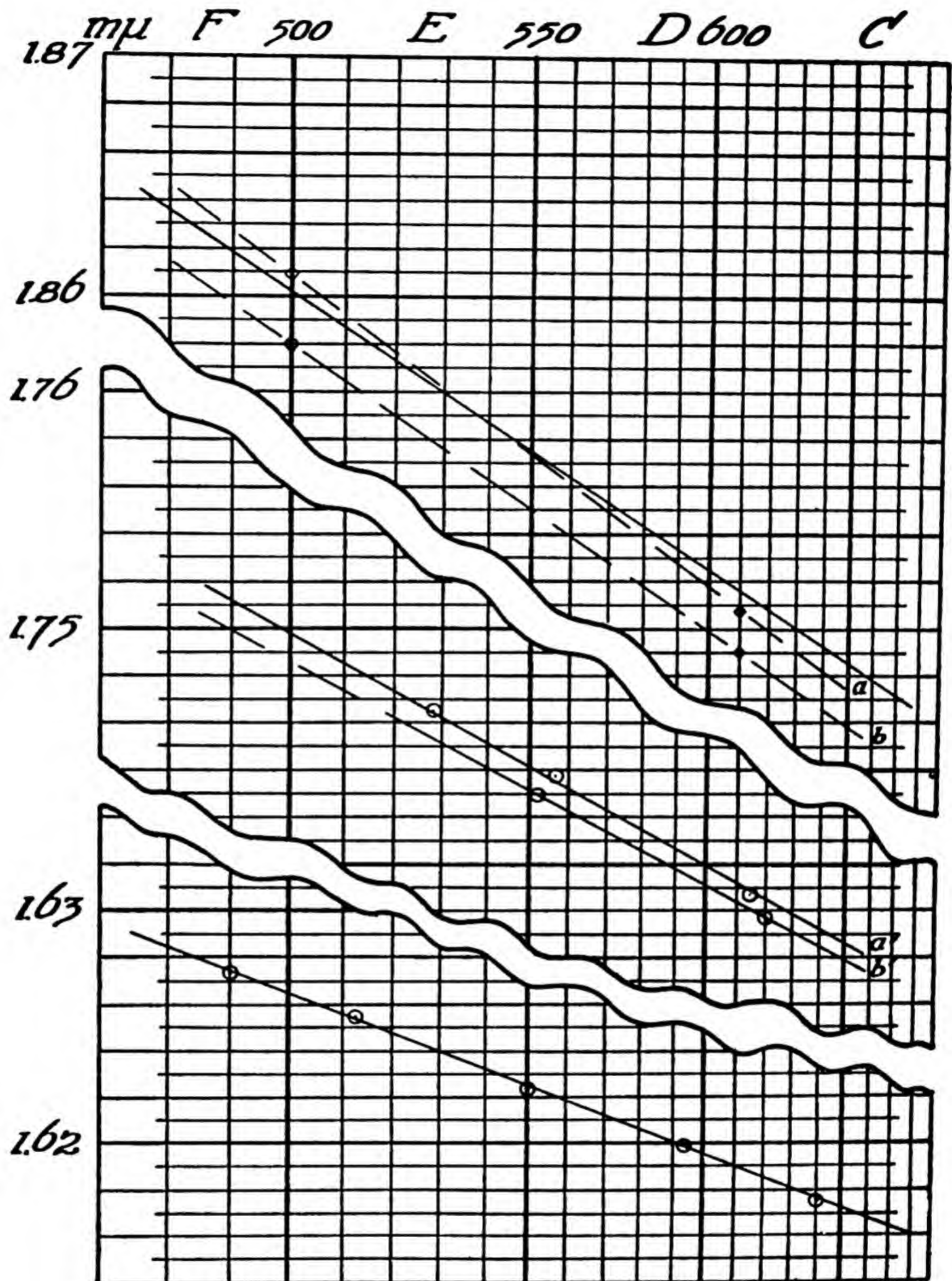
FIGURE 88.—*Extrapolation of data (Table 9) for crystal of smithsonite*

To learn the value of ω which lies above all standard liquids. Separate mounts in different liquids were used for ϵ and ϵ'. Two separate determinations show the accuracy to be expected from so wide an extrapolation on separate grains. The upper solid line is the curve obtained by the minimum deviation method.

and separate mounts were used—that is, ϵ and ϵ' were not measured on the same grain. Two separate determinations were made by the immersion method. Both are given to show the degree of accuracy expected. The respective curves are designated "a" and "b". In addi-

TABLE 9a.—*Double variation data*

(Fig. 38)

MINERAL LABORATORY

Mineral. Smithsonite .... Locality ....

I. E–W	— —		Orientation: α		
N–S	45° W		β		
O. A. 1	Horizontal		γ		
2			I. V.		
	2V–1	2V–2	Immersion Liquid	7	
O. V.	(	(	Hemispheres	1.649	
O. E–W			Zero Values: Mic	0$^\delta$	
M	(	(	O. V	90°	
2V					

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor'	Ray #3
E	32+	32+	512	1.6122	.0133	1.6255						
"	39	39–	490	1.6089	.0184	1.6273						
"	25	25	550	1.6164	.0059	1.6223						
"	17	18+	593.5	1.6204	–.0005	1.6199						
"	11	13	640	1.6236	–.0061	1.6175						

tion to this, the ω value was determined by minimum deviation and is represented in the figure by a solid line in the upper part. The maximum error even under these unfavorable conditions is between .002 and .003.

Having illustrated the benefits and methods of using one liquid mount to obtain all the desired data on a given crystal grain, it is apt to point out an observation which this type of work is checking daily—namely, that many crystals differ in composition in different parts of the crystal to an extent not generally realized. Several crystalline materials are already recorded as so varying, but the indications are that the proportion of such crystals is truly great. Figures 34-37 inclusive are all measurements of olivine from the same hand

TABLE 9b.—*Double variation data*

(Fig. 38—curve a′)

MINERAL LABORATORY

Mineral. Smithsonite .... Locality ....

I. E–W	— —		Orientatiou: α	
N–S	— —		β	
O. A. 1	42° S (36.7° Cor)		γ	
2			I. V.	
	2V–1	2V–2	Immersion Liquid	1
O. V.	(	(	Hemispheres	1.649
O. E–W			Zero Values: Mic	0°
M	(	(	O. V	90°
2V				

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor·	Ray #3
E′	24	24	614	1.7428	−.0042	1.7386	4° N	O.E–W				
"	33 −	32	556	1.7370	.0068	1.7438	"	"				
"	39 +	38	528	1.7326	.0139	1.7465	"	"				
							3.9°	Corrected				
				90	−(36.7	+3.9)	=49.4°					
							.5°	Correction for high birefringence				
							49.9°	E	.1202	610	.1075	1.8467
							"	E	.1233	500	.1111	1.8609

specimen of dunite. The results were all checked and are believed to be accurate beyond ±.001. Indices on opposite sides of one grain differed by as much as .003. There was no noticeable strain in the mount; such strain usually appears as double refraction in the glass cover slips used. The extent and importance of this apparent chemical variation can be especially well explored by the technique being described.

TABLE 9c.—*Double variation data*

(Fig. 38—curve b')

MINERAL LABORATORY

Mineral. . . . . Smithsonite . . . . .Locality. . . . .

I. E–W	— —		Orientation: α		
N–S	40° W (41° Cor)		β		
O. A. 1	Horizontal		γ		
2			I. V.		
	2V–1	2V–2	Immersion Liquid	1	
O. V.	(	(	Hemispheres	1.649	
O. E–W			Zero Values: Mic	0°	
M	(	(	O. V	90°	
2V					

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray #3
E'	36	36	551	1.7350	.0080	1.7430	49°	E				
E'	25	25	620	1.7429	.0052	1.7377	''	E				
				41°+8.3° =			49.3°	E				
							.5°	Correction for birefringence				
							49.8°	E	.1220	500	.1095	1.8580
							49.8°	E	.1194	610	.1066	1.8450

A word of caution may be added about using Wright's diagram for calculating the third index of a biaxial crystal from two indices and the optic angle (Pl. 11). If, as in Table 6 for example, $\beta - \alpha$ and V are known, it must not be assumed that the value of V about the acute bisectrix is to be used. It may be seen from the orientation data that the acute bisectrix is vertical and that α is vertical, which makes the crystal negative. If on Plate 11 the value of V used is 43.5° too high a curve for γ is obtained, and the crystal is positive. It is to be remembered that in a positive crystal β is closer to α than

to γ. In Figure 35 and Table 6, $\beta - \alpha = .0152$. Following the instructions on Plate 11, "if the ordinate is $\beta - \alpha$ then 2V is measured about γ." Since α is vertical in the example, 2V is taken as 93°, and $\gamma - \alpha$ is .0289. The incorrect and correct curves for V are given in the figure.

The Instruments Employed:

The successful use of the method depends, among other things, on the proper use and understanding of the instruments. The apparatus consists of (1) an arc lamp as a source of light, (2) a monochromator which provides light of variable wave length, (3) a petrographic microscope and universal stage, (4) a refractometer, preferably without Amici prisms, and (5) a water circulation system which keeps the microscope mount and refractometer mount at the same temperature (Pl. 3, fig. 1; Pl. 4).

The arc lamp is the prime source of light and is directed into the collimator of the monochromator, where a considerable part of the light is lost since at the entrance of the collimator the first slit excludes a large part of the light. It is well therefore to focus the arc rather sharply on this slit. On the other hand, a short focus is to be avoided since convergent rays do not reach the prism of the monochromator. The telescope tube of the monochromator, carrying the second slit, is directed to a swinging mirror. In one position this directs the monochromator beam to the microscope mirror and in another to the refractometer mirror. Another swinging mirror between the arc lamp and the monochromator, when swung in, cuts off the monochromator and directs the white light of the arc directly to the swinging mirror between the microscope and the refractometer. This permits the use of white light of high intensity on the microscope where it is needed for the initial orientation of a crystal. After the crystal is oriented the mirror in front of the arc is swung out, and the microscope is illuminated with monochromatic light. Without this arrangement it would be necessary to redirect the arc lamp, which is not convenient. Adjustment of the arc to the monochromator must be done carefully. This entire arrangement makes it possible to bring the crystal and liquid into agreement in refractive index on the microscope stage and then to read the index on the refractometer for the same wave length of light.

The arc lamp may be operated on alternating or direct current. Better illumination is obtained from a direct-current arc which also lights much more readily and burns more steadily and more quietly. The intensity of illumination is a most important consideration

when using a monochromator since a large part of the light is lost. The most common difficulties experienced in obtaining good arc lamp illumination are: (1) The polarity of the lamp is reversed in using a direct-current lamp and may be simply corrected by reversing the
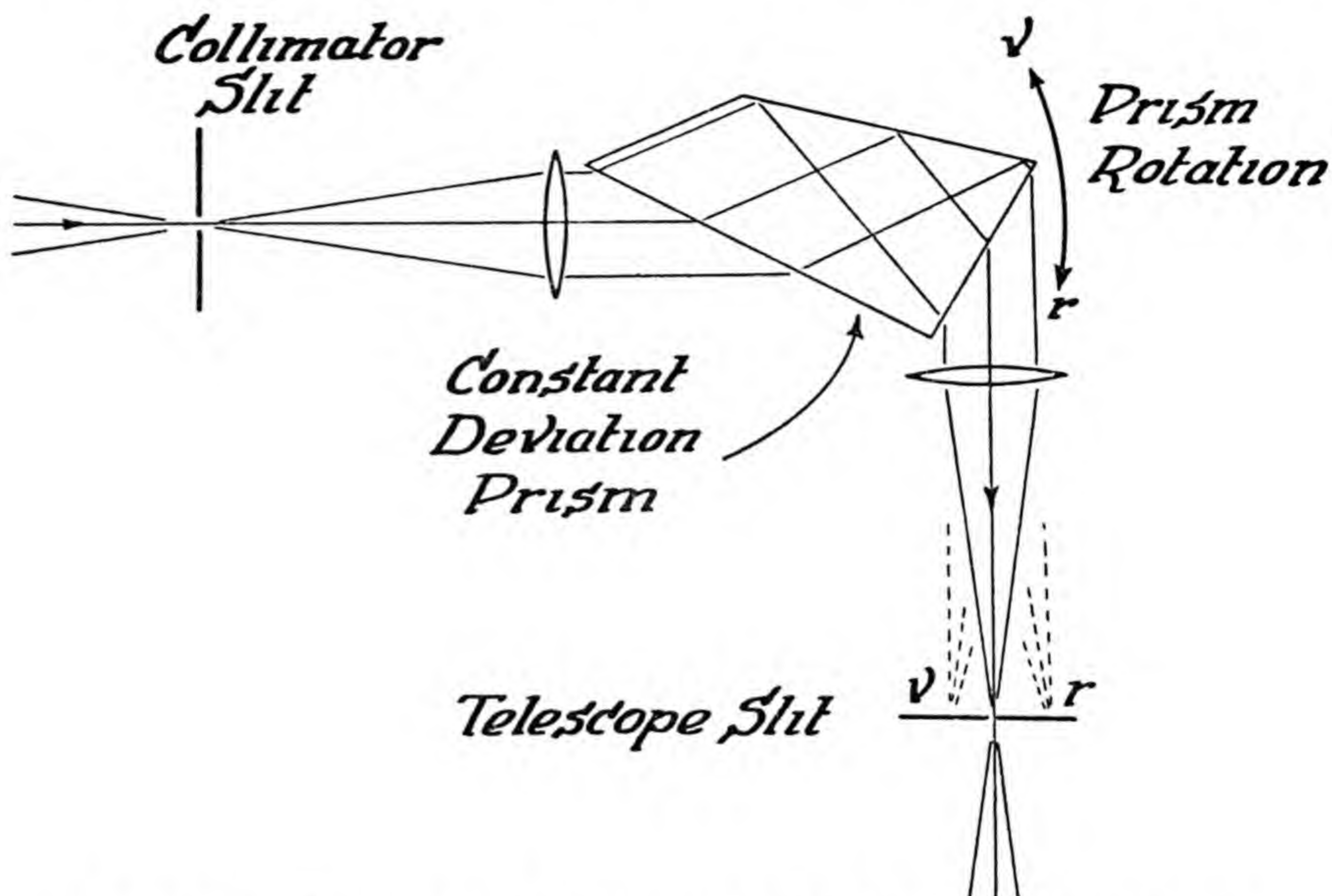
FIGURE 39.—*Diagrammatic representation of a modern monochromator*

The feature of this instrument is its constant deviation prism. The incident and refracted rays from such a prism—that is, the collimator axis and the ocular axis—are always 90° apart when the prism is rotated to change the wave length.

wires at the lamp or plug connection. Most lamps sold for this purpose are so-called 90° arcs, one carbon being horizontal and the other vertical. The horizontal carbon is the larger and faces the lens of the lamp. When viewed through the dark window the larger carbon should appear brighter when the current is flowing in the proper direction. With alternating current there is no difference in the brightness of the two carbons, which are the same size. (2) The vertical carbon is too high, obstructing the light from the horizontal carbon. The carbons should be kept about ¼ inch apart and equally advanced. If the vertical carbon is too low then the crater forms on the lower side of the horizontal carbon, reducing the illumination. (3) A periodic difficulty is patchy illumination, especially after the light has passed through the monochromator. This is commonly caused by a white deposit which forms

on the rear side of the arc lamp lens. It is readily soluble in water. A lamp which is being used steadily should be so cleaned every 2 or 3 weeks. This deposit forms faster from German-made carbons than it does from American-made carbons. (4) The annoying flickering which has characterized American-made carbons and established a strong prejudice against them has finally been corrected. They are now at least the equal of those of foreign make.

The monochromator (Fig. 39) should be carefully selected according to the operator's needs. There is a considerable difference in the monochromators of different manufacturers, expressed mainly in the manner of manipulation. Since the collimator slit is small some adjustable reflecting device is helpful in front of the collimator tube, otherwise it is difficult to align the arc lamp beam accurately with the optical axis of the monochromator collimator. Also, since most arcs "wander" somewhat as they burn and therefore require adjustment, it is simpler to keep the beam adjusted with the help of a reflector. The Leitz monochromator has such a reflector built into the instrument. In using a Bausch & Lomb monochromator it is well to use an accessory mirror which clamps on the front end of the arc lamp. In this way the optical axis of the arc lamp and of the monochromator collimator are set about 90° to each other. The reflector also enables the operator to see easily whether the white light beam is focused on the monochromator squarely and sharply. These precautions relate to light intensity, which is early found to be closely related to the accuracy of the final results in the determination of refractive indices.

No rule can be given for setting the slits to determine the breadth of the monochromatic beam, in terms of wave length. A balance must be found between the intensity of the original light source and the intensity of the monochromator beam at the microscope. The stronger the source the narrower may be the wave length of the monochromatic beam. It should be emphasized however that, before increasing the illumination at the microscope by adjusting the slits, the operator should be sure that the maximum illumination is being obtained from the white light source. If another instrument is not available for checking, suitable results may be had by opening wide the ocular slit and closing the collimator slit until the spectrum appears in rich unblended colors. On closing the ocular slit one color band alone is chosen. Further adjustments of intensity should be made mainly with the ocular slit. This slit should be so constructed that its control moves both jaws at once, otherwise
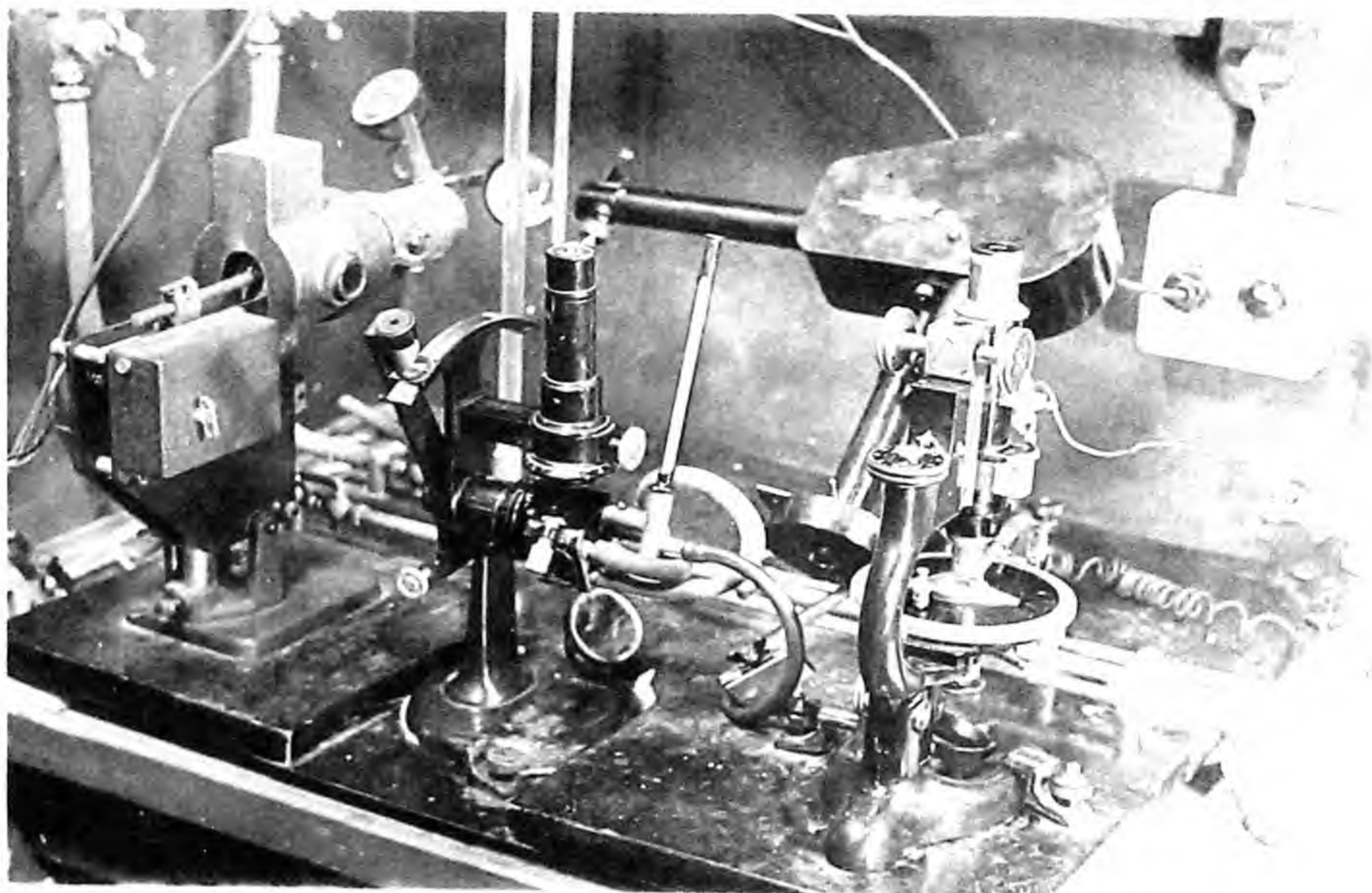
FIGURE 1. BAUSCH & LOMB DOUBLE-VARIATION EQUIPMENT IN DEPARTMENT OF SOILS,
UNIVERSITY OF WISCONSIN
(Photograph by D. S. Turner.)
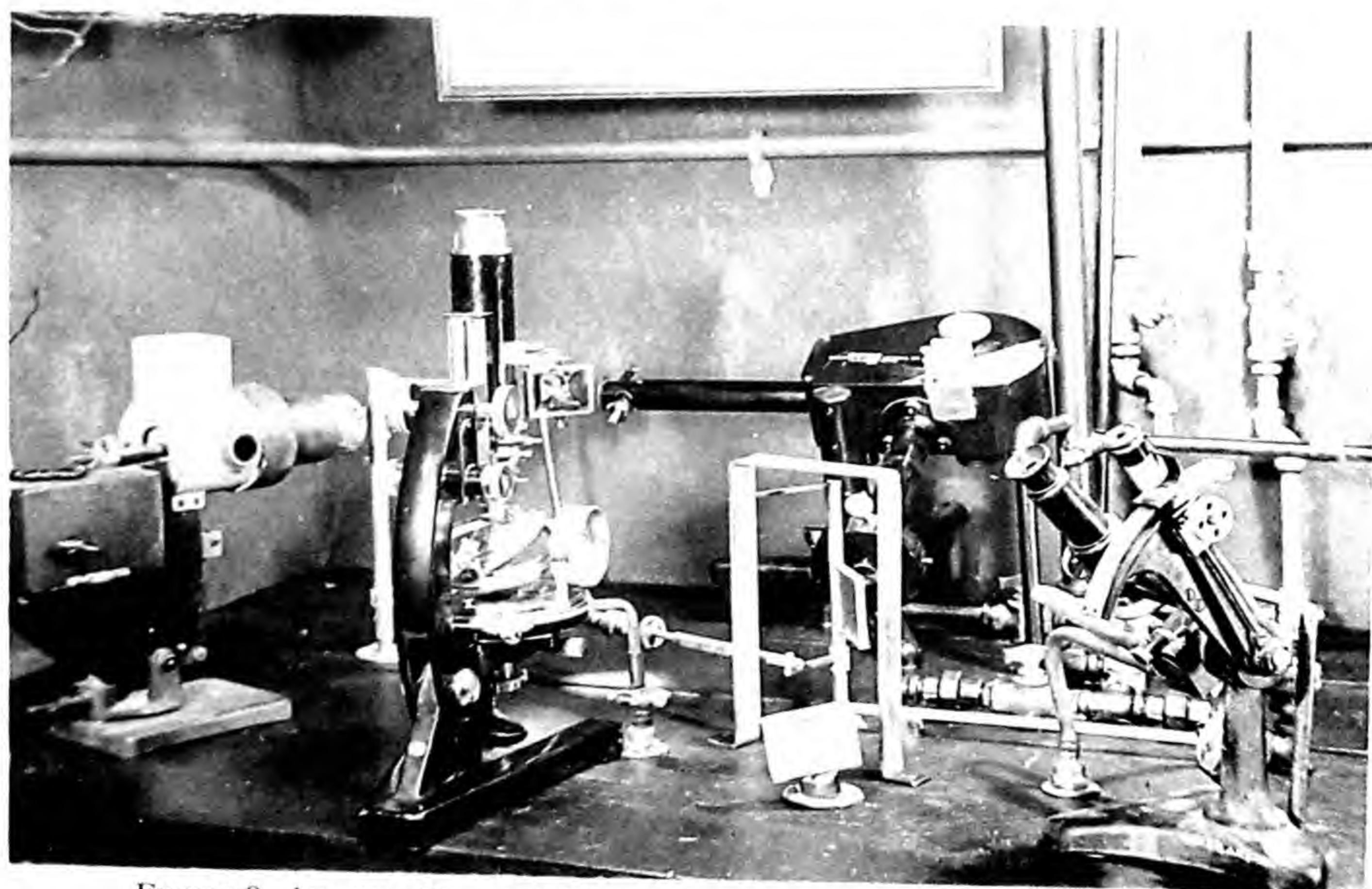
FIGURE 2. ANOTHER UNIT FOR DOUBLE VARIATION AT UNIVERSITY OF WISCONSIN
(Photograph by D. S. Turner.)

DOUBLE VARIATION APPARATUS
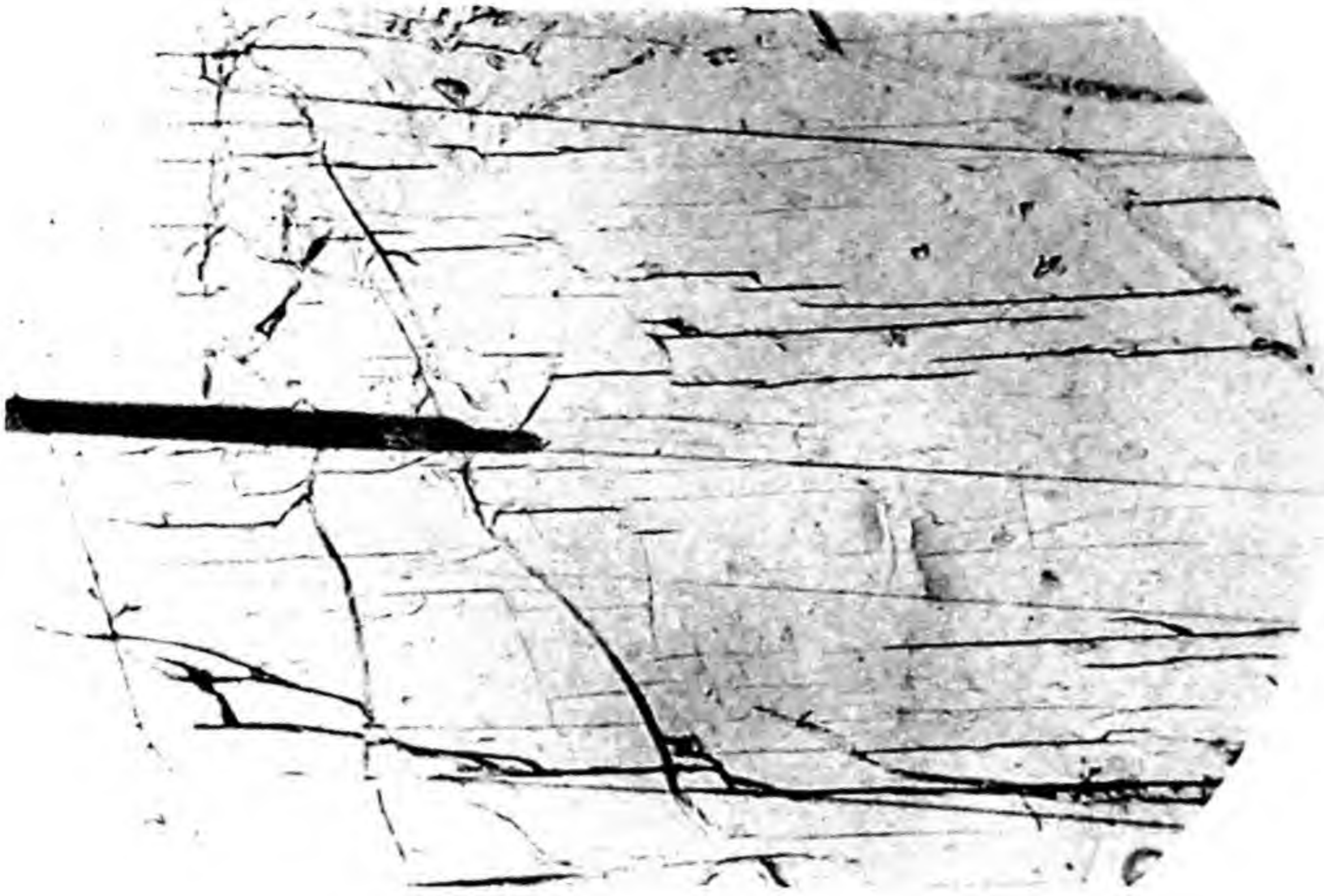
FIGURE 1. PLAGIOCLASE
CRYSTAL
From near Split Rock Point,
Minn. (x90). See Figure 67.
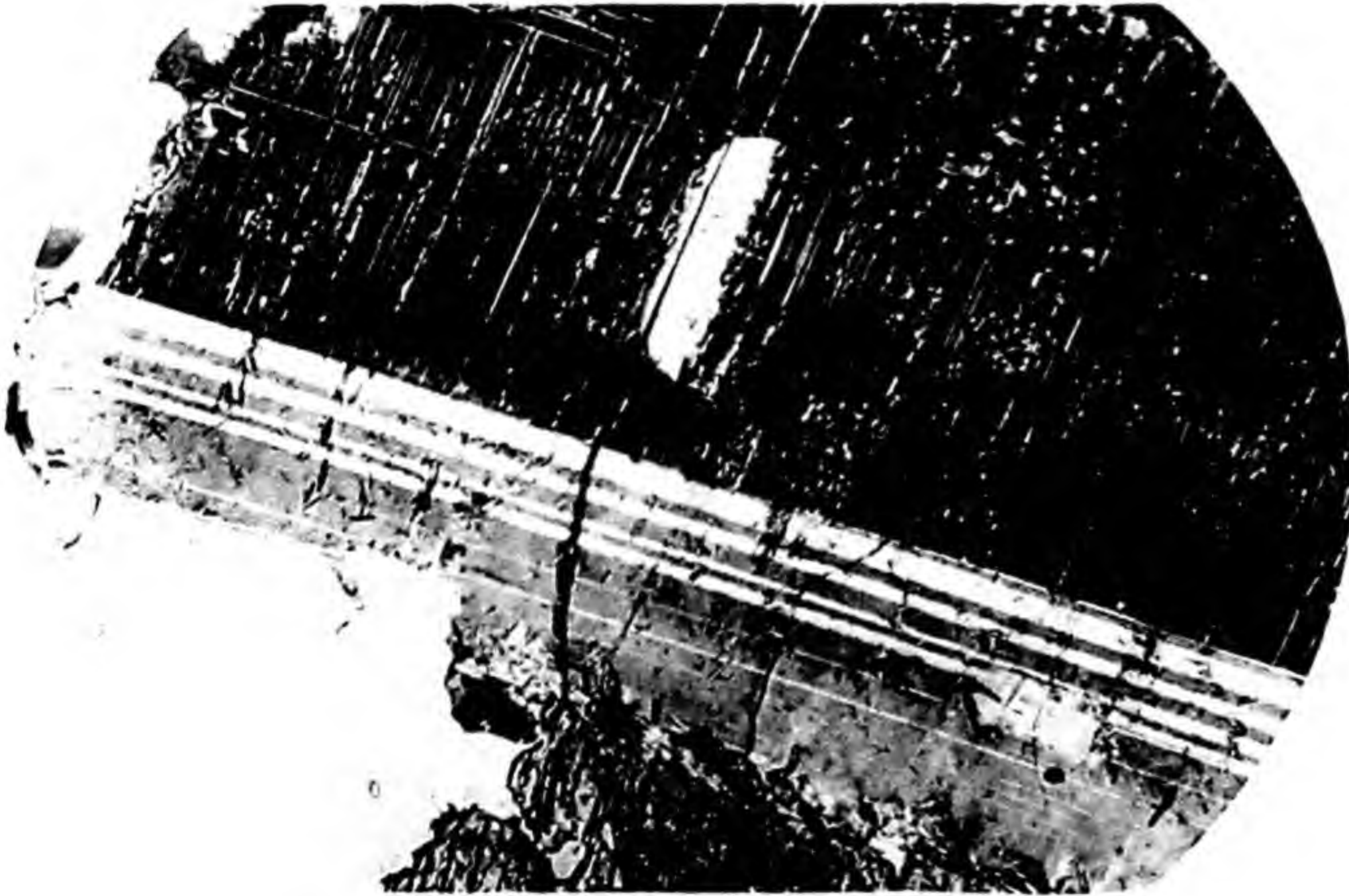
FIGURE 2. PLAGIOCLASE
CRYSTAL
From near Dunbar, Mari-
nette County, Wis. (x150).
See Figure 68.
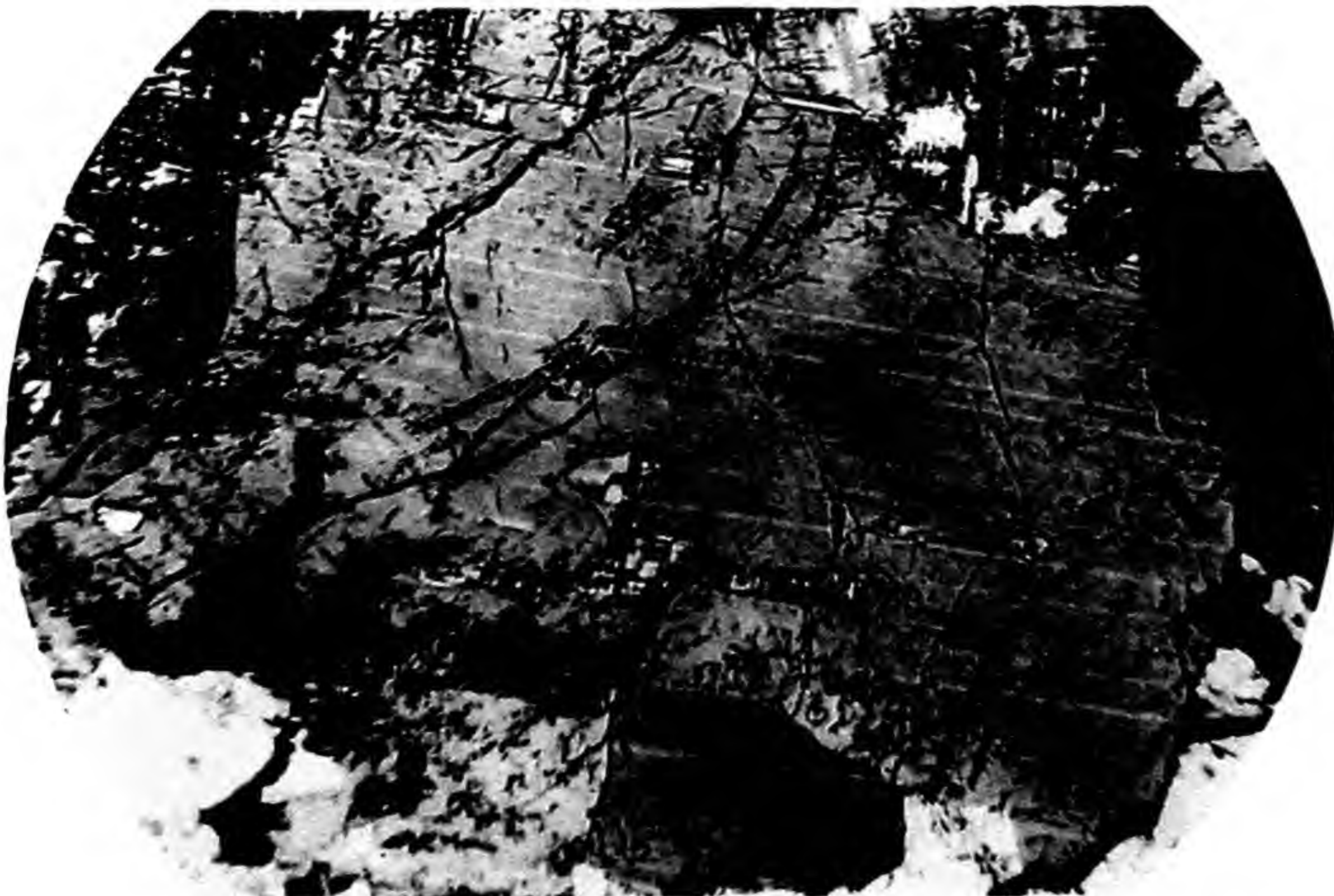
FIGURE 3. PLAGIOCLASE
CRYSTAL
From hybrid rock 8 miles
east of Wittenberg, Wis.
(x47). See Figure 61.

NARROW FELDSPAR TWINS

to change intensity is to shift the spectral band without making a corresponding change in the scale of the instrument.

It is of course important that the monochromator should be set accurately so that its scale reading may be properly interpreted. To check the instrument it should be removed from the double variation set-up and used as a spectroscope on light of known wave length. In the Bausch and Lomb monochromator that means replacing the eye lens which is not used when illuminating a microscope. Sodium light is the most conveniently obtained in the laboratory—place a small fragment of halite on a Méker burner; after the halite has once melted it will not decrepitate again and may be used as a source of monochromatic light indefinitely. Place this flame in front of the collimator of the monochromator, focus the eye lens on the cross hairs, close the collimator slit until the yellow band seen is narrow, and turn the prism until the yellow line coincides with the cross hairs. The scale should read slightly over 589mμ, or the instrument must be adjusted. The Bausch and Lomb monochromator is provided with a depressible pin which holds the scale fast while the prism may be turned by the control knob. Turn the scale to 589mμ, depress the pin which holds the scale, and turn the control knob until the spectral line for sodium coincides with the cross hairs. Then the instrument should read correctly as a spectroscope for other wave lengths. If the collimator slit is very narrow two lines may be seen (589.0 and 589.6mμ), but since the instrument is to be used as a monochromator we are more interested in having the collimator slit somewhat open. Set this slit at the reading which was found suitable for microscope illumination. Close the ocular slit to the same size as viewed through the instrument, then holding the scale at 589mμ as before turn the prism until the two slits coincide. This last step is unnecessary in instruments in which the telescope slit jaws both move on adjustment. The Bausch & Lomb monochromator as supplied with double variation equipment carries a special ocular adapted from a larger instrument in which both jaws move on slit adjustment, and the slit may be moved laterally by a thumb screw. To set this instrument make the adjustments outlined for a spectroscope, open the collimator slit the desired amount for microscope purposes, and adjust the ocular slit for width and position to coincide with the visible band. Although this is an extremely convenient method, in a student laboratory the thumb screw is disturbed all too frequently.

The Leitz small monochromator scale is not graduated in wavelength divisions, but from 0—100. The instrument must therefore

be calibrated and a curve constructed. For this purpose it is best to standardize the readings with another spectroscope, but satisfactory results may be obtained by using light of known wave lengths such as the sodium flame or the helium spectrum tube and the

Field of View

Upper Prism

Ray of Grazing Incidence

Frosted Surface

Lower Prism

Paper Thin Film of Liquid
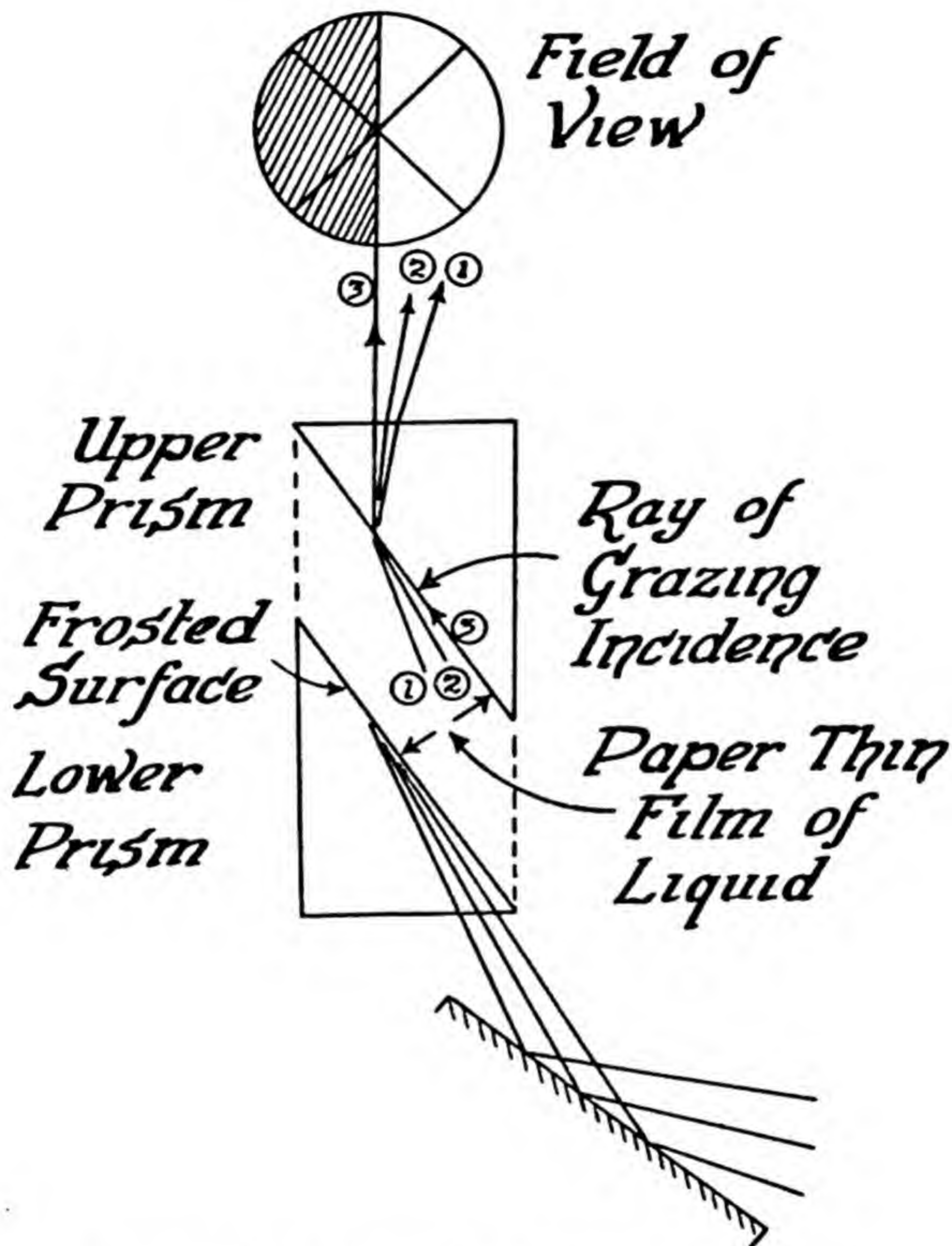
FIGURE 40.—*Schematic diagram of the Abbé refractometer*

Showing the principle of its operation and the proper position of the prism relative to the mirror to get the best illumination. This position should be observed carefully.

hydrogen tube. These give enough points for a close approximation to the correct curve.

The refractometer is the Abbé type (Fig. 40). It is accurate to ±.0002 for a single reading under proper illumination. The Amici prisms which fill the lower part of the tube are solely for use with white light. It is said that they slightly impair the accuracy of reading. *When using monochromatic light the Amici prism drum should be set to read 30 for all wave lengths.* Or, better still, the
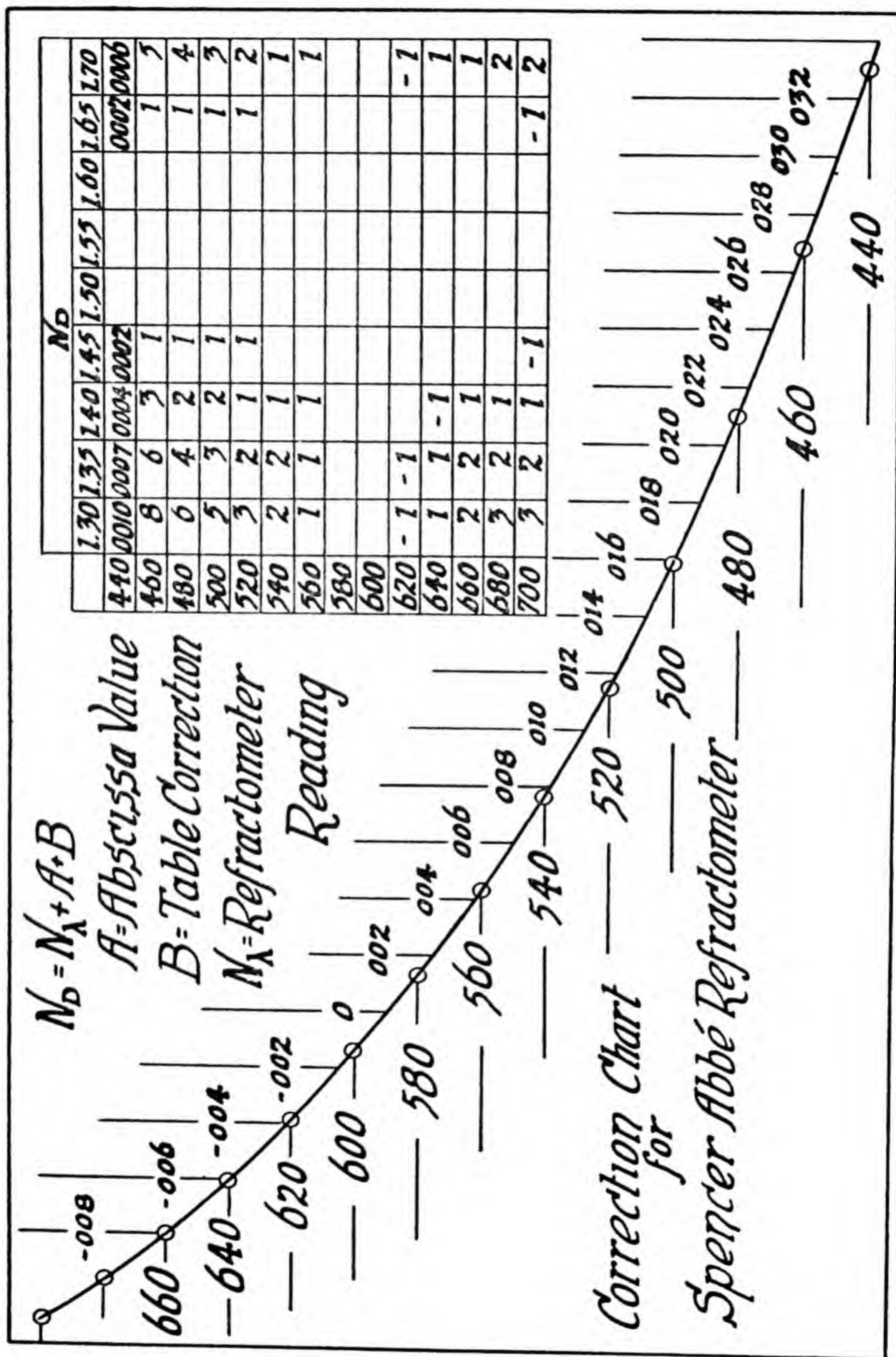
FIGURE 41.—*Abbé refractometer correction chart*

Designed by the Spencer Lens Co. for the instrument when it is used with monochromatic light. Such a chart is provided with most Abbé refractometers by the manufacturer on request.

Amici prisms may be removed. American manufacturers supply the Abbé refractometer at reduced cost without the Amici prisms.

The reading of the refractometer scale is to be corrected for the wave length of monochromatic light used, on a correction curve supplied with the instrument. The lower prism is solely a source of diffused illumination for the upper (polished) prism, providing, especially, light of grazing incidence for the upper prism, which is the light which defines the border line between the light and dark field. It is obvious that the higher the refractive index of the liquid the less the refracted ray deviates from the path of the ray of grazing incidence—that is, the greater is the angle of refraction. But the shorter the wave length of light the greater is the deviation and the smaller the angle of refraction unless the liquid is one of very high dispersion (as is the glass of the prisms). Accordingly, the scale of the instrument reads higher indices in one direction, but as the wave length of light is shortened the empirical reading lies in the other direction. When the instrument is illuminated with white light, the border between the light and dark field is ordinarily a spectral band. Adjustment of the Amici prisms reduces this band to a sharp line. When the Amici prisms are set at 30 their effect is cancelled. To determine refractive indices at various wave lengths with monochromatic light the Amici prisms are set at 30, and direct readings are made. However, as indicated above, these readings are correct only for the sodium wave length for which the instrument is designed. A correction is applied for the wave length used in order to obtain the refractive index of the liquid for this wave length. This correction is obtained from the manufacturer's curve (Fig. 41) and is a plus value for the wave lengths shorter than that for which the instrument scale is constructed (589.3mμ) and a minus value for longer wave lengths. The smaller tabular correction is necessary because the top face of the upper prism is a plane surface and not curved.

The ray which defines the border of the light field is the ray of grazing incidence on the upper prism. If this ray is faint the border of the light field is indefinite, and the index reading is inaccurate. To correct this condition change the inclination of the tube with respect to the source of light—that is, the mirror. The contact plane of the polished and frosted prism surfaces should nearly include the path of the light from the mirror. In this way the critical ray is intensified.

The refractometer should be checked occasionally, especially if it is used by many people, as in a student laboratory. For this

purpose a glass of known refractive index for sodium light is supplied with the instrument. This glass has two optical, mutually perpendicular surfaces. The larger surface is placed with liquid contact on the polished prism surface. Use a liquid of higher index than that of the glass. The other polished surface is directed toward the light source, a sodium flame. A frosted glass should be introduced in the light path in front of the instrument to facilitate bringing the illumination to grazing incidence. Bring the border line to the cross hairs and read the scale. There is no correction usually since the glass index is apt to be given for the sodium wave length. If the stated index does not read correctly on the scale adjust the instrument. Set the scale at the proper reading, attach a small screw driver to the screw in the side of the tube which controls the position of the cross hairs, and turn this screw until the cross hairs coincide with the border line. The instrument should now read properly for other values of refractive index. The lower prism of the Spencer Abbé refractometer may be removed conveniently at the hinge. This materially simplifies checking the instrument and reading the indices of solid substances in general.

The uppermost and lowermost surfaces of the refractometer prisms periodically should be cleaned since liquids spread to them, especially the lower one, and dust accumulates. Dirty surfaces result in less intense illumination and an indefinite border line. Ordinarily these optical conditions may be attributed to faulty illumination and corrected by adjusting the mirror and the inclination of the tube to the mirror. Failing in this, examine the prism surfaces.

Sometimes a broken line appears in the refractometer, usually due to unsatisfactory cleaning of the instrument when removing the liquid last used. Even the cement holding the glass prisms in their mounts absorbs enough liquid to cause occasional trouble. It is well routinely to clean the instrument with acetone or something equally good. Never use a dirty or dusty cloth. The polished prism surface should be protected from scratching, as the sharpness of the border line depends largely on the quality of this surface. A double line is also produced when the swinging prism is not properly closed after adding liquid. The two prism surfaces must be parallel.

The Spencer Lens Company makes two Abbé refractometers for higher indices—one to 1.79 and one to 1.84. Since the glass in these instruments is a softer lead glass (flint glass) their surfaces should be cleaned only with lens paper and some cleaner such as acetone. Also avoid allowing high-index liquids, which almost invariably contain free iodine, to stand on the glass longer than necessary since

the lead of the glass tends to combine with the iodine to form a film of lead iodide. Separate curves for correction of readings made with monochromatic light are provided for these instruments which are not the same as the curve for the standard (1.71) instrument.

All Abbé refractometers are less accurate near the upper end of their index range, the border line being decidedly indefinite.

Discussion of the microscope will not be attempted here, except insofar as its use for this purpose involves special technique. (1) Correct illumination includes accurate centering of the light so that the light path coincides with the axis of the microscope. Otherwise, rotation readings on horizontal axes of the universal stage are apparent but not true. To obtain centered light, direct the light beam squarely on the mirror of the microscope (which if mounted on a swinging arm should be centered), introduce the Bertrand lens, and center the beam on the cross hairs. (2) The light source, especially when using monochromatic light, produces a very narrow beam which in terms of microscope illumination is "parallel light". Parallel light is essential for good refractive index determination by means of the Becke line, especially in an objective of low numerical aperture. Since low-power objectives are mainly used with the universal stage, this parallel light makes accurate results possible. In fact, even with a low-power (No. 1 or 40 mm.) objective (N.A. 0.1) the Becke line effect on the universal stage is outstandingly satisfactory. The coarse adjustment is to be used for observing the Becke line effect, since the low-power objective has a long working distance. (3) Sometimes just the opposite effect is wanted—namely, convergent light or at least enough convergence to fill the back lens of the objective. Real convergent light in the ordinary sense is impossible with any of the objectives for the universal stage on account of their low numerical aperture. However, the numerical aperture of any of these objectives is considerably increased when used in conjunction with a hemisphere. By introducing a frosted glass immediately below the polariser, the light is sufficiently diffused to fill the objective. A holder for a frosted glass may be obtained as an easily applied accessory. In this way an interference figure may be obtained on the universal stage. Open all diaphragms and introduce the Bertrand lens (or remove the ocular). Ordinary precautions should be taken to insure a good figure as in ordinary microscope work, such as to close the Bertrand or ocular diaphragm to exclude other grains, focus the Bertrand lens, or center the grain. The resulting figure is not so satisfactory as that obtained with an objective of high numerical aperture (N.A. .85) in that less of the figure

is obtained although it does fill the field.   However, the figures are sufficient to assist in orientation for those to whom figures appeal. It is most unnecessary to obtain a figure in universal stage work. (4) Magnification has been discussed in an earlier section.   (5) The polarizer should be rotated if necessary so that its vibration direction is N-S.   This better accommodates the inclination of the mirror in the customary arrangement, and it is also much more convenient for making rotation readings of refractive index by use of a horizontal axis, preferably the outer E-W.   (6) In addition to the customary diaphragms above the polarizer and above the Bertrand lens the microscope should have a diaphragm below the polarizer either built in or as an accessory attachment so that more nearly parallel light may be obtained.   This and the diaphragm in the objective already mentioned serve to sharpen extinction and are closed during final check rotations in orienting crystals on the universal stage.   A powerful light source is needed when using them since they cut out a large part of the transmitted beam.   Another diaphragm in the ocular is also helpful in excluding all but the centered crystal being studied. It is desirable to close this when attempting an accurate orientation of a crystal in thin section, especially a crystal of low birefringence, since variation in the interference colors of adjacent crystals lessens the sensitivity of the eye to the important, comparatively delicate variations in interference colors of the crystal of interest which is near extinction.   (7) The microscope stage *must* be provided with a clamp to hold it in any position of rotation.   It should either carry two verniers making it possible to read its position always, even when the universal stage covers one vernier as is not uncommon, or it should be large enough that the universal stage cannot cover the vernier. The former is the new Leitz method; the latter is adopted on the new Bausch & Lomb microscope.

The water circulation control is embodied in the base designed to hold these instruments (Fig. 42).   It consists of a hot and cold water intake from each of which leads (1) an overflow which is allowed to run slowly to prevent stagnant water in the leads to the apparatus when one or both are not being used, (2) an offtake to the equipment.   These offtakes join in a T beyond which the temperature of the water depends upon the setting of the offtake valves; this is the temperature control of the equipment.   Beyond the T the water enters a standard which is open at the top and provided with another overflow.   In this standard the desired head is maintained by means of the overflow.   The overflow also prevents stagnant water in the standard.   The main purpose of the standard how-

ever is the removal of bubbles before the water reaches the micro-
scope. Water leaves the standard near the base, passes over the bulb
of a thermometer, and enters the water cell on the universal stage.
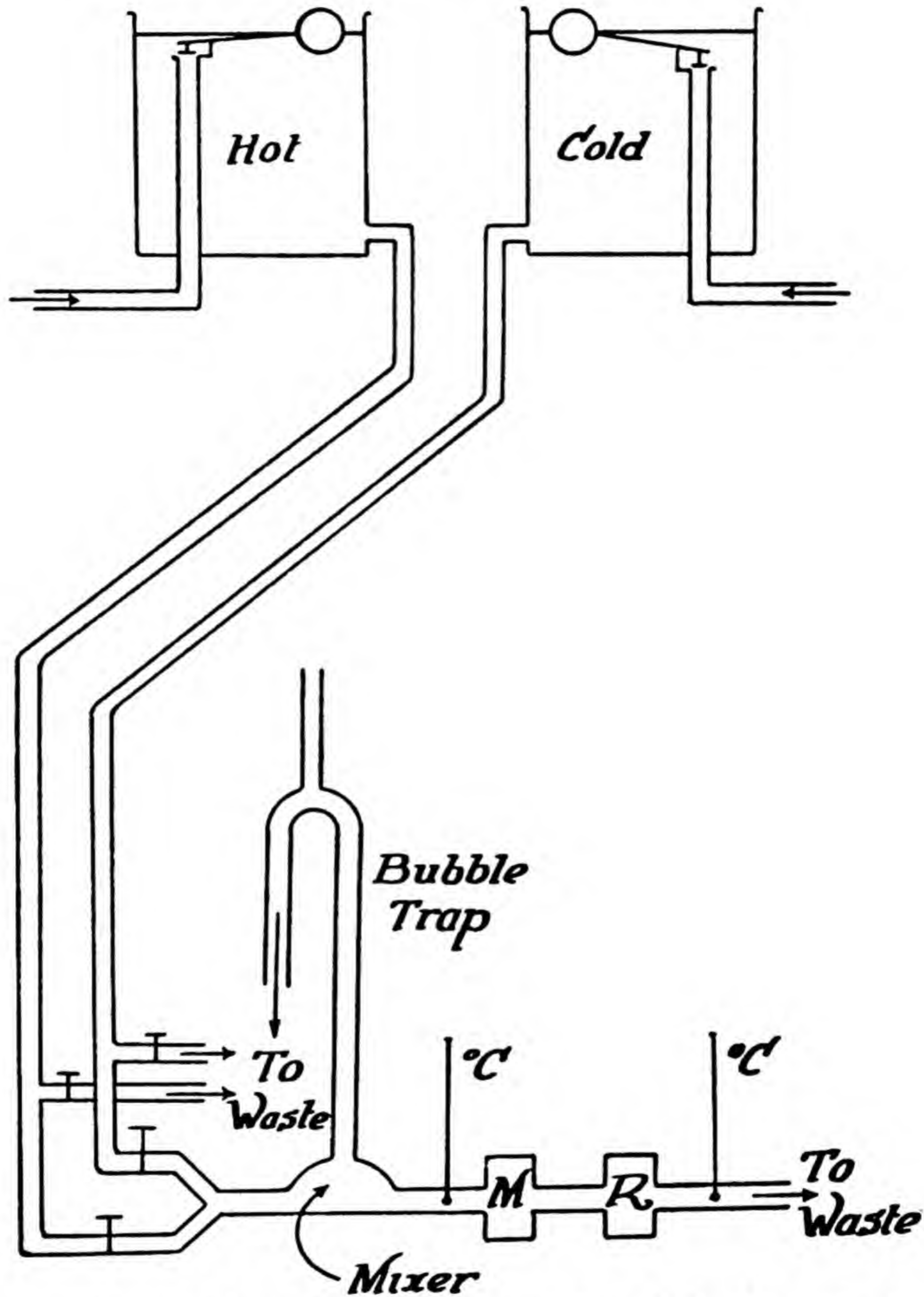

FIGURE 42.—*Diagrammatic representation of double-variation
apparatus temperature control*

The water should enter the cell at the inner nipple, cross the center of
the cell, and return around the edges. This course is less inclined to
trap bubbles that pass the bubble standard. Very light rubber tubing,
sufficiently flexible that it offers little pull, should be used on the water
cell.

Water leaves the cell and enters the refractometer. This course should not be reversed since at extreme temperatures the temperature of the stage lags slightly more behind the water than does the refractometer. In the refractometer the water passes over the bulb of another thermometer and then to the waste. The two thermometers should be so chosen that they agree regardless of their accuracy. They indicate to the operator the efficiency of the water circulation. By means of water circulation the temperature may be set *above or below* room temperature. The electrically heated stage on the market will heat, but it takes time to cool. Water circulation is also effective in keeping the immersion liquid on the universal stage and on the refractometer at the same temperature. It is important to maintain an adequate head (the maximum preferred) in the standard. Since the same liquid is mounted on both the microscope and refractometer and since the same water circuit which controls the temperature of the microscope mount also controls the temperature of the refractometer prisms, therefore when the crystal and liquid agree in refractive index on the microscope the index of the the liquid is read on the refractometer at the same temperature and with light of the same wave length.

In the writer's laboratory the hot and cold water mains lead directly to two tanks from which water is drawn off to the double variation tables. The tanks are equipped with ball-cocks and each tank has an overflow. This system has been adopted as the most satisfactory of several tried. The system is diagrammatically represented in Figure 42.

Vigfussen (1940) recently reported a water heating system where a supply of hot water is not available and must be provided at the apparatus. He uses an immersed heating coil which operates on the lighting circuit.

Avoid allowing the inside of a water cell to dry out as this precipitates on the walls the solid matter in solution in the water, impairing transparency.

The Bausch and Lomb specially designed base, with instruments is shown Figure 1 of Plate 4. Two of the double variation tables made and used in the Mineral Laboratories at the University of Wisconsin are shown in Figure 1 of Plate 3 and in Figure 2 of Plate 4.

Chapter 6

General Discussion of Feldspar Twinning and Twin Laws

THE methods of routine petrography do not make possible the identification of the prevailing twin laws. Though some petrographers estimate the twin laws on the basis of general appearance and even report such results, their results are not reliable. Except for those who use the universal stage, therefore, few become familiar with any but three or four of the laws most frequently discussed in the classroom, and of these the Baveno is not common. Standard textbooks in English treat the subject of feldspar twinning with a brevity consistent with its practical importance in present-day petrography and ignore the fundamental causes of twinning and its practical significance. Literature on feldspar twinning is now quite abundant, but deals largely with the mere statistical occurrence of the different twin laws. This brief summary assumes a general knowledge of the principles of twinning.

Twinning axes bear an orientation relationship to the optics of a crystal just as do the other crystallographic elements. Fedorow and later Nikitin and his associates accumulated information on this relationship and plotted it in stereographic form, to be used as we shall use face poles in Chapters 8 and 9. This procedure reveals (1) the twin law as indicated by the migration curve on which the point falls, and (2) the composition of the crystal in terms of the anorthite content as indicated by the position on the migration curve. To carry out this procedure, however, the general classification of the law must be determined first.

There are three main composition faces (010), (001), and the rhombic section. The less common Baveno twin has (021) or (0$\bar{2}$1) as composition face. Other twins are reported and may be regarded as fact, but are sufficiently rare that they are not encountered in ordinary work. The twinning axes are either perpendicular to the composition faces or lie in them. This in fact is the first basis of classification.

A twin is described by giving its composition face and the twinning axis. The composition face is one of the crystallographic planes mentioned and the twinning axis is described as (1) perpendicular to one of these faces, (2) as an edge between two faces, or (3) as perpendicular to an edge between two faces. Type symbols used

104   The Universal Stage

to express these conceptions are (1) ⊥ (001), the Manebach law; (2) [001] or c, the Carlsbad law; (3) ⊥ [001] in (010) or ⊥ c in (010) the albite-Carlsbad law. These are also designated respectively in groups as representing (1) the normal law, (2) the edge law, and (3) the edge normal law. We shall here refer to these three types as (1) normal, (2) parallel, and (3) complex twinning laws, following the pioneer workers. We may define them as follows.

A normal twin is one in which the twinning axis is perpendicular to the composition face. One unit is rotated 180° about this axis with respect to the other unit.

A parallel twin is one in which the twinning axis lies in the composition face and is parallel to an edge between two faces. Again the rotation is 180°.

A complex twin is one in which the twinning axis lies in the composition face and is perpendicular to the edge between two faces. The rotation is 180°. The same effect as one rotation on a complex twinning axis may be obtained by making two rotations equivalent to those of a normal and parallel twin on the same composition face; hence the name applied by Fedorow—complex twin. These three directions are of course mutually perpendicular.

A normal twin is distinguished from a parallel or complex twin on the compilation sheet. If the twinning axis falls on or near the pole of the composition face the twin is normal. If on the other hand the twinning axis falls on or near the composition face the twin is parallel or complex. The determination of the pole and its location on the stereographic projection will be discussed later. A normal twin may also be distinguished from a parallel or complex twin on the microscope (see Chapters 8 and 9) as follows. Make the composition face vertical and parallel to a nicol and rotate on a horizontal axis perpendicular to the composition face. If the adjacent lamellae change color together the twin is normal, otherwise it is parallel or complex.

A parallel twin can be distinguished from a complex twin only by a determination of the attitude of the twinning axis relative to the other crystallographic elements—that is, by its position on a migration curve stereogram. As will be brought out shortly some complex and parallel twin laws are quite indistinguishable.

The migration curve stereograms are all based on the same general principles but are variously used by different operators. The procedure adopted here employs the optical orientation which is always available and easily obtained rather than the crystallographic orientation which is too often doubtful. Further, since a stereogram com-

plete with all the desirable information is somewhat confusing, the stereograms here used are divided into two groups: One group consists of face poles for 010, 001, 021, 0$\bar{2}$1, and the rhombic section (marked "Per"); the other group is given over exclusively to parallel
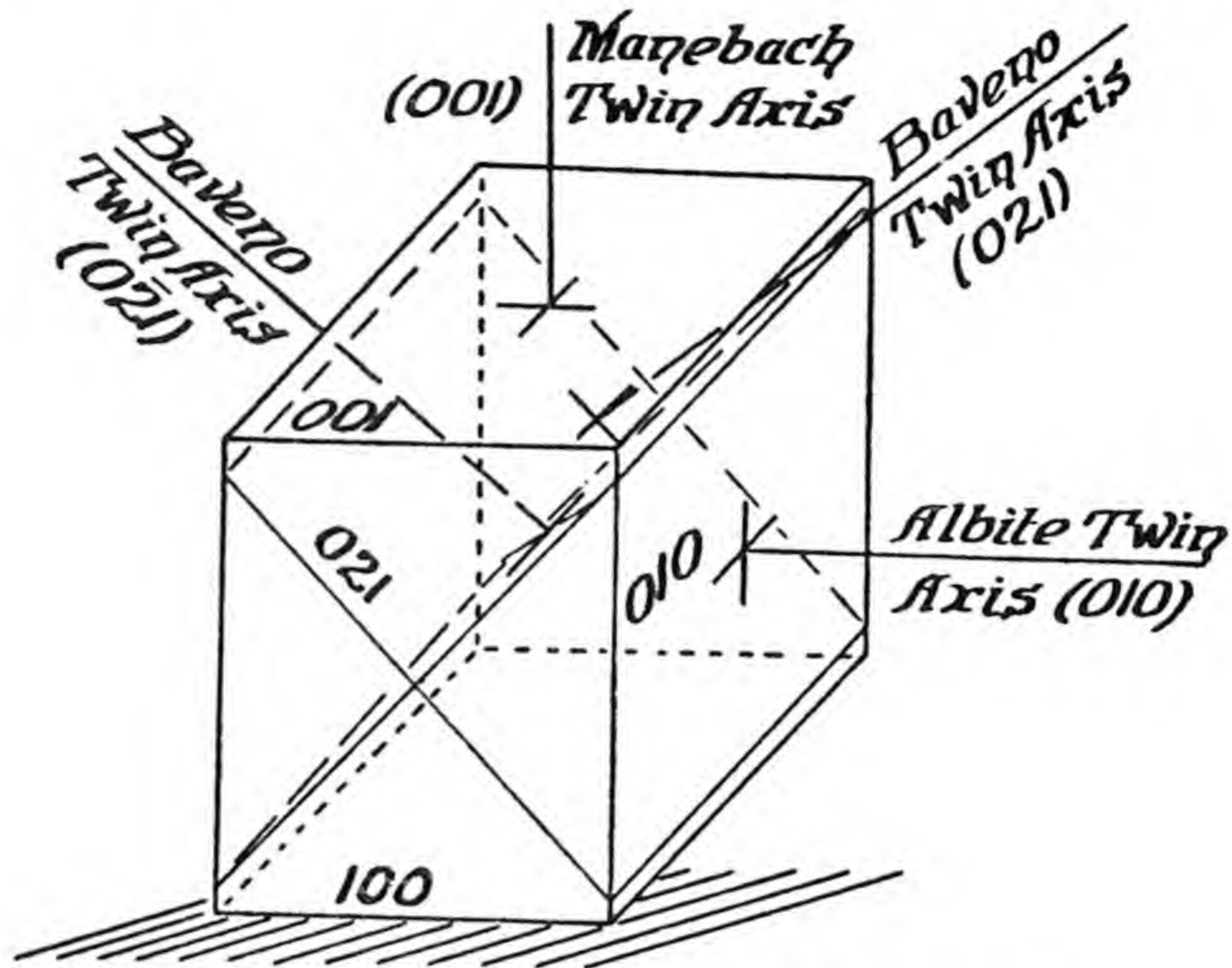
FIGURE 43.—*Normal twin axes of plagioclase*

and complex twinning axes. This fits in with the instrumental procedure which leads first to the recognition of the twin as normal or parallel (or complex). For further convenience each of these two groups is divided into three—the three possible optical orientations. This makes it unnecessary, once a crystal is oriented, either to reorient it to the usual reference position (*i.e.*, β is parallel to the axis of the microscope) or to rotate a stereographic projection of the orientation obtained, to agree with the reference projection. The stereograms are given in Plate 12.

The procedure then is direct. The orientation obtained is plotted stereographically, and the twin law is classified as either normal or parallel (or complex). If the law is normal reference is made to Figures 1, 2, or 3 of Plate 12, according to whether α, β, or γ is vertical in the projection just constructed. Similarly, if face poles are being determined the same plates are to be used since the normal twin axes coincide with the face poles.

If the twin law is parallel or complex Figures 4, 5, or 6 of Plate 12 are to be used according to whether α, β, or γ is vertical. There are no face poles on these figures.

In Figures 7, 8, and 9 of Plate 12 are similar data recorded for the potash feldspars. All the data for this plate are Nikitin's (1936, p. 98 *et seq.*).

Rarely does a point fall squarely on a migration curve. In Figure
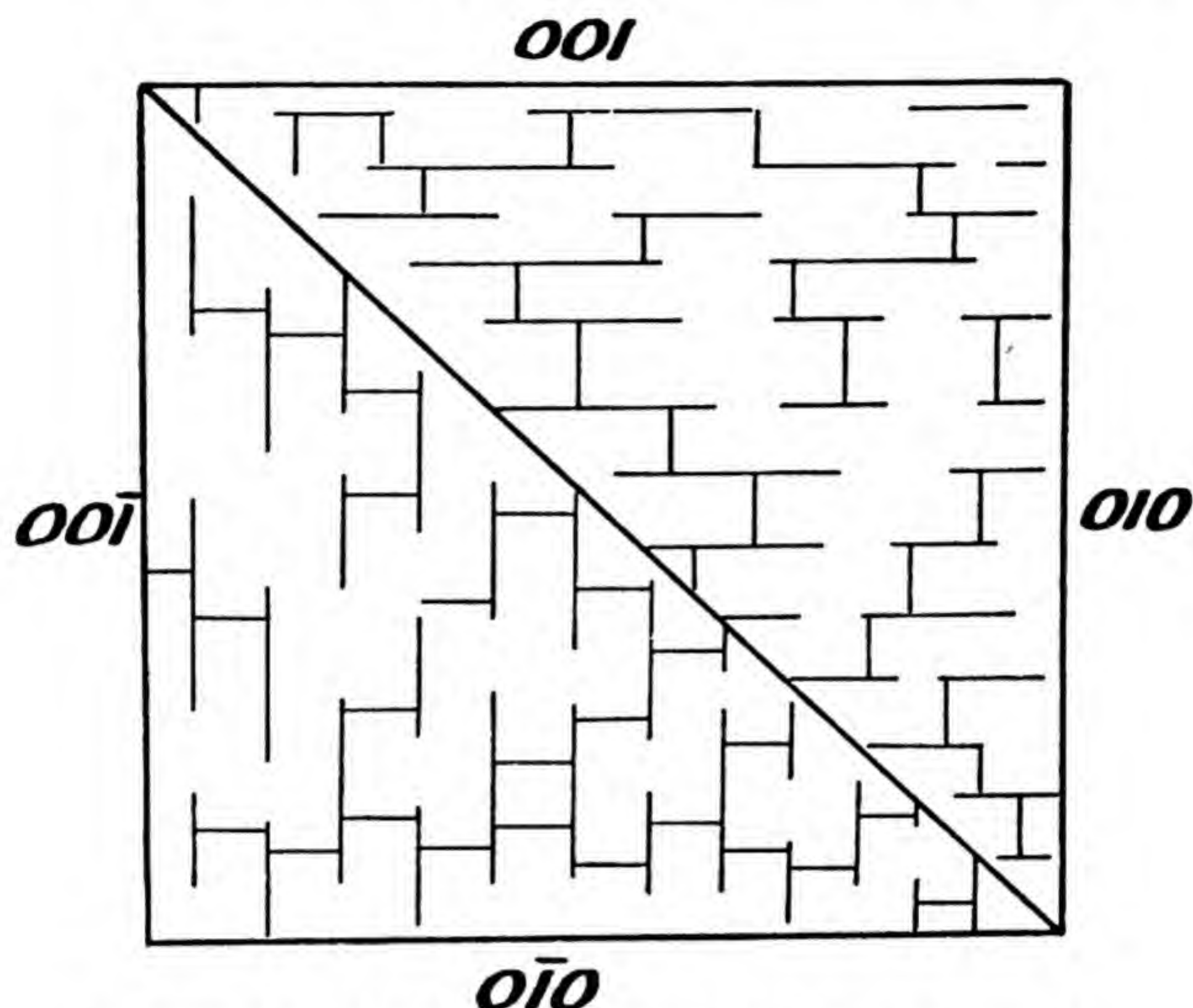
FIGURE 44.—*Baveno twin in relation to cleavage*

6 of Plate 7 unit three shows irregularities in interference colors which may be seen in the figure. The quality of the results obtained on this unit depends on which part of the crystal is oriented. Other crystals show a more sharply delimited irregularity which on study by the five-axis method (Chapter 8) may be revealed as the difference between a parallel and a complex twin.

Normal twin laws. There are three normal twin laws (Fig. 43): (1) the albite law in which the composition face is (010) and the twin axis is normal to it; (2) the Manebach law in which (001) is the composition face and the twin axis is normal to it; (3) the Baveno law in which (021) is the composition face and the twin axis is normal to it. There are of course two possible Baveno twins corresponding to the two domes (021) and (0$\bar{2}$1). Manebach twinning is expressed as two individuals—a simple twin. Albite twinning is ordinarily repeated giving multiple twinning. Baveno twinning is usually simple, is much less common than the others and may be recognized readily because the composition face is diagonal to the cleavages or other composition faces. However, the other reference planes must be made approximately parallel to the axis of

the microscope, otherwise one of them may appear diagonal to the other (Fig. 44).

In all twins one individual is regarded as having been rotated 180° about the twinning axis relative to the adjacent individuals.
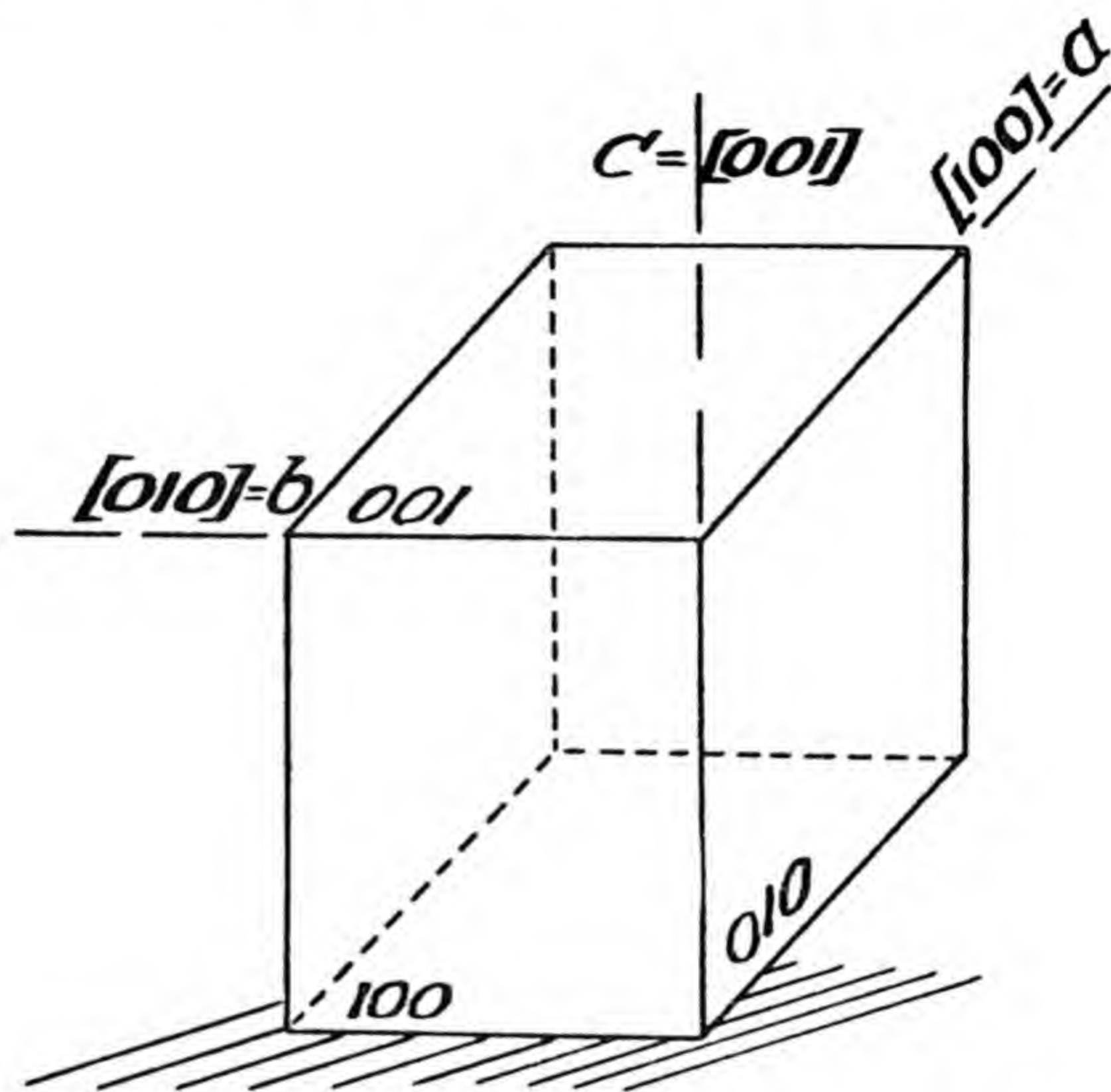
FIGURE 45.—*Parallel twin axes of plagioclase*

For each axis there are two possible twins (A and B) according to which of the pinacoid faces (of the two that define the axis) is the composition face. Those having (100) as composition face are either theoretical or very rare. Therefore the Ala law, **a**, alone of the parallel laws is recognized here as two laws—Ala A and Ala B.

Parallel twin laws. There are five parallel twin laws: (1) the Carlsbad law in which (010) is the composition face and the twin axis is parallel to the edge (010) (100) and expressed as [001] or **c** (Fig. 45). Since the twin axis lies in the composition face (010) the rotation is different from that which leads to a normal twin. As illustrated in Figure 46, in a model, one individual must be removed from contact with the other individual to accomplish the rotation, whereas in a normal twin the two individuals remain in contact at the composition face. In a normal twin the composition face is therefore also the twinning plane; in a parallel twin the twinning plane (normal to the twin axis) is of theoretical interest only. (2) the Ala A law in which (001) is the composition face and the twin axis is parallel to the edge (001) (010) and is expressed as [100] or **a**. (3) the Ala B law in which (010) is the composition
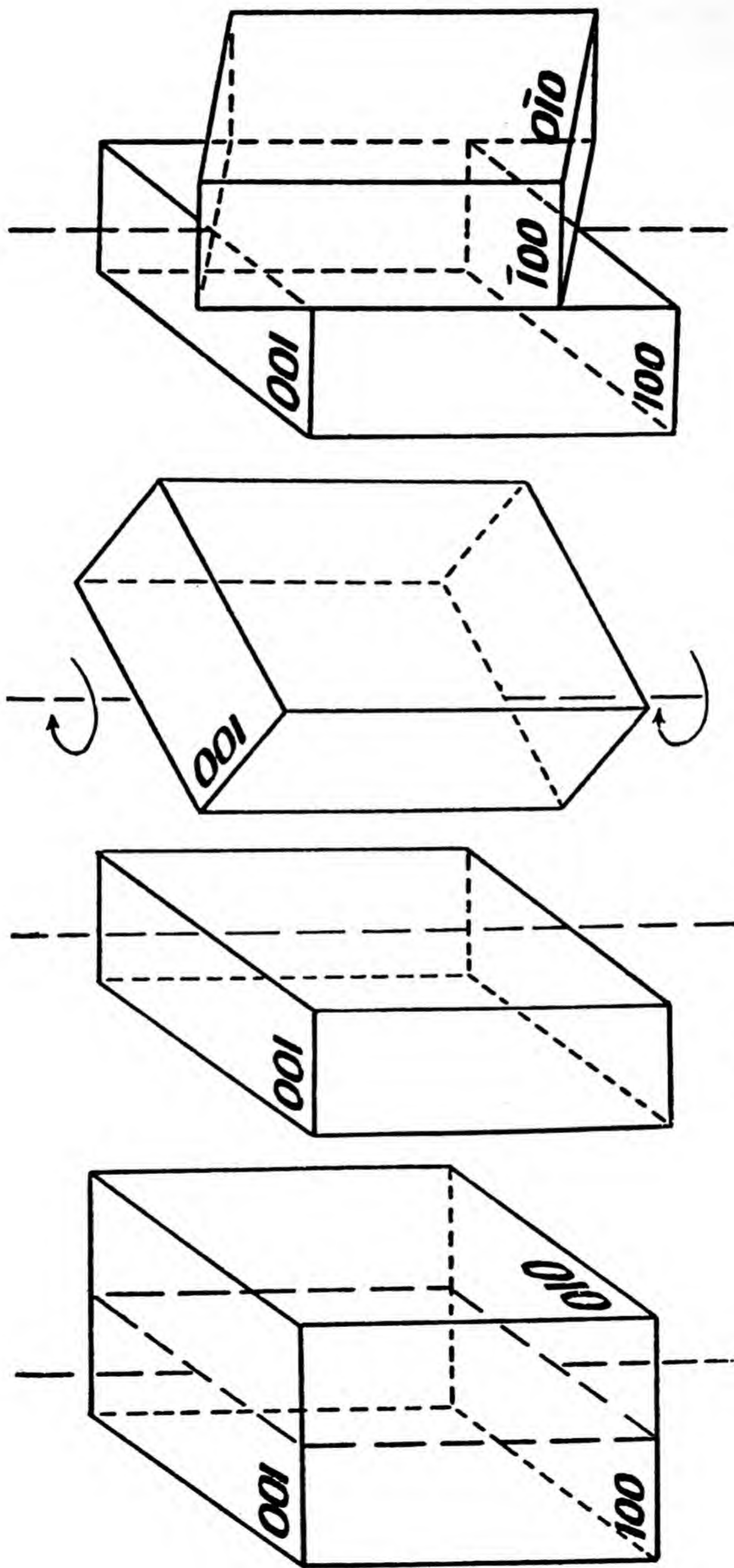
FIGURE 46.—*Rotation to produce a Carlsbad twin*

face and the twin axis is again **a**. (4) the acline law in which (001) is the composition face and the twin axis is parallel to the edge (001) (100) and is expressed as [010] or **b**. (5) The pericline law in which the composition face is the rhombic section and the twin axis
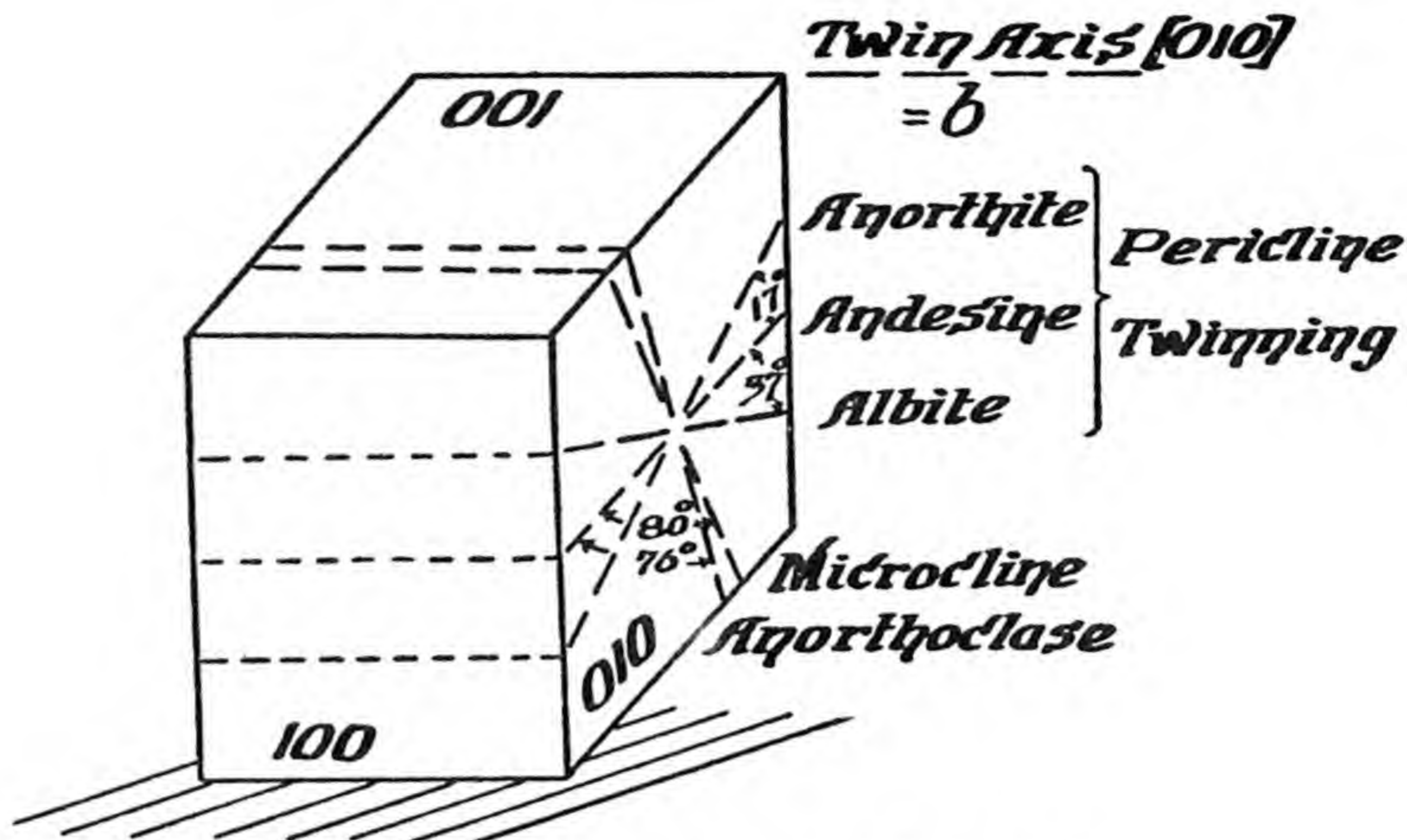
FIGURE 47.—*Rhombic section of plagioclase*

Composition face of pericline twinning, shown in relation to three pinacoids. Also shown is the microcline type composition face, which with albite twinning produces the characteristic gridiron structure.

is **b** as for acline twinning. The rhombic section is inclined to the base (001), 37° for albite, and is inclined in the other direction, 17° to the base for anorthite (Fig. 47). For intermediate plagioclases it is inclined at intermediate angles and for andesine it is parallel to the base. Therefore acline and pericline twinning are identical for this plagioclase and are indistinguishable by present methods for adjacent plagioclases. This is shown in Plate 12 by the proximity of the curves for the pericline composition face and (001).

Complex twin laws. There are four complex twin laws, two of which are indistinguishable, for practical purposes, from two of the parallel laws. (1) The albite-Carlsbad law. The composition face is (010), and the twin axis is perpendicular to the edge [001] or **c** and of course lies in the face (010). This twinned position may be reached theoretically either by rotation of one individual relative to the other on the twin axis or by two twinning rotations, one according to the albite law and one according to the Carlsbad law— hence the chosen name of the law as albite-Carlsbad complex.

This twin axis is described as ⊥ [001] in (010) or ⊥ **c** in (010) (Fig. 48). (2) The albite-Ala law. The composition face is (010), and the twin axis is ⊥ [100] in (010) or ⊥ **a** in (010). The twin position may be reached either by one rotation on this axis or by two rota-
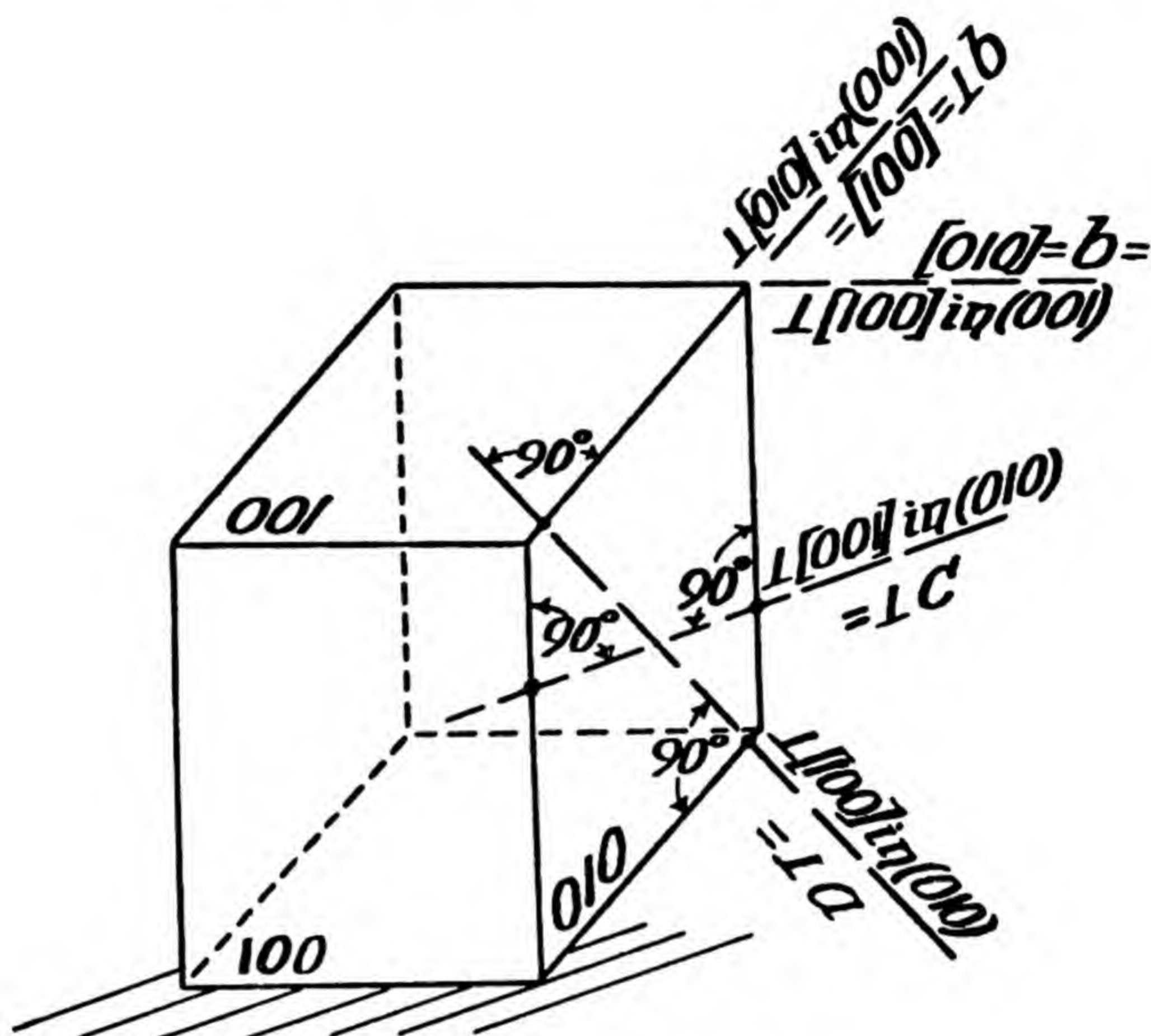
FIGURE 48.—*Complex twin laws*
Two are real and two are rarely and difficultly recognized.

tions—one on the axis ⊥ (010), the albite law, and one on the axis **a**, the Ala law.

The following two complex twins are of theoretical interest only, since they are ordinarily indistinguishable from parallel twins. (3) the Manebach-Ala law. The composition face is (001), and the twin axis is ⊥ **a**. As the name implies this twin may be produced by a combination of Manebach and Ala twinning also. Reference to Figures 45 and 48 and to Plate 12 will show the virtual identity of this law and the acline law. (4) the Manebach-acline law. The composition face is (001), and the twin axis is ⊥ **b**. A combination of Manebach and acline twinning will also produce this twinned position. This twin axis is usually indistinguishable from the Ala axis **a**.

The various twin laws are distinguished by a knowledge of the twin axes and the composition faces. As already indicated this may

best be studied in stereographic projection in which orientation relationships are clear. Obviously normal twins are easily distinguished from each other. So also the parallel twins and the complex twins may be distinguished from others of the same type, but
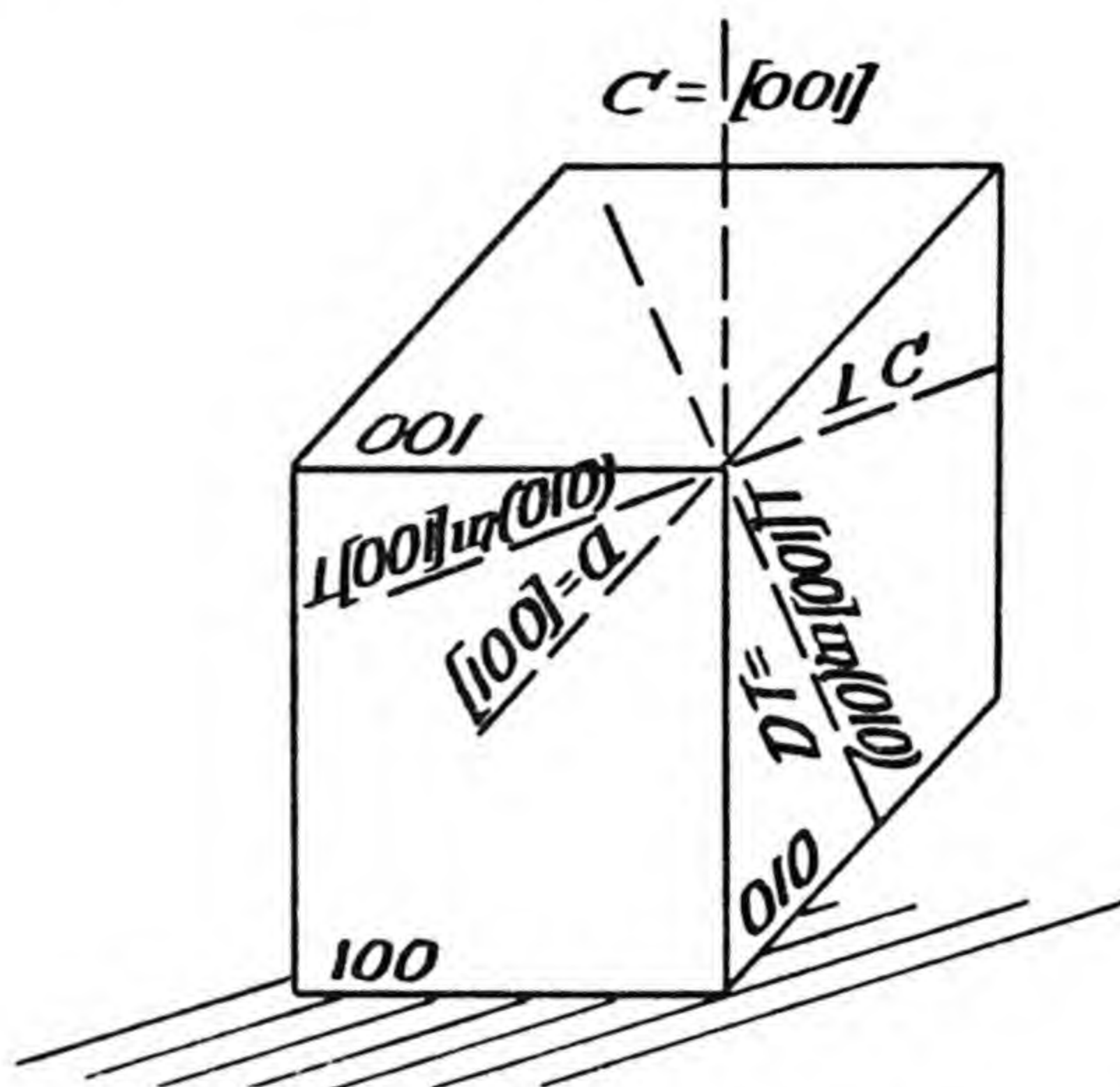
FIGURE 49.—*Parallel and complex twin laws having (010) as composition face*

These are readily distinguished because of the spatial distribution of their axes.

they may not always be distinguished from each other. Normal twins may be recognized in two ways, thereby removing all possible confusion. On the microscope, if the composition face is parallel to the axis of the microscope and to the north-south cross hair, on rotation on the outer east-west axis the contiguous lamellae of a normal twin will remain equally bright. In stereographic projection if the twin axis is found to be perpendicular to the composition face the twin is normal. A normal twin axis, which lies near a twin axis of another type, therefore offers no difficulty.

In *both* parallel and complex twins, the twinning axis lies in the composition face. Also, on the microscope, if the composition face is made vertical and north-south as was suggested above for a normal twin, a rotation on the outer east-west axis produces a relative difference in birefringence colors in adjacent lamellae. We are therefore dependent on the position of the twin axis relative to the optical orientation to distinguish these twins, though other factors

are sometimes helpful. In Figure 49 are shown the relative positions of the twin axes for Carlsbad, Ala, albite-Carlsbad, and albite-Ala twin laws. These axes are widely enough separated that they may be distinguished with ease. In Figure 50 are shown the relative
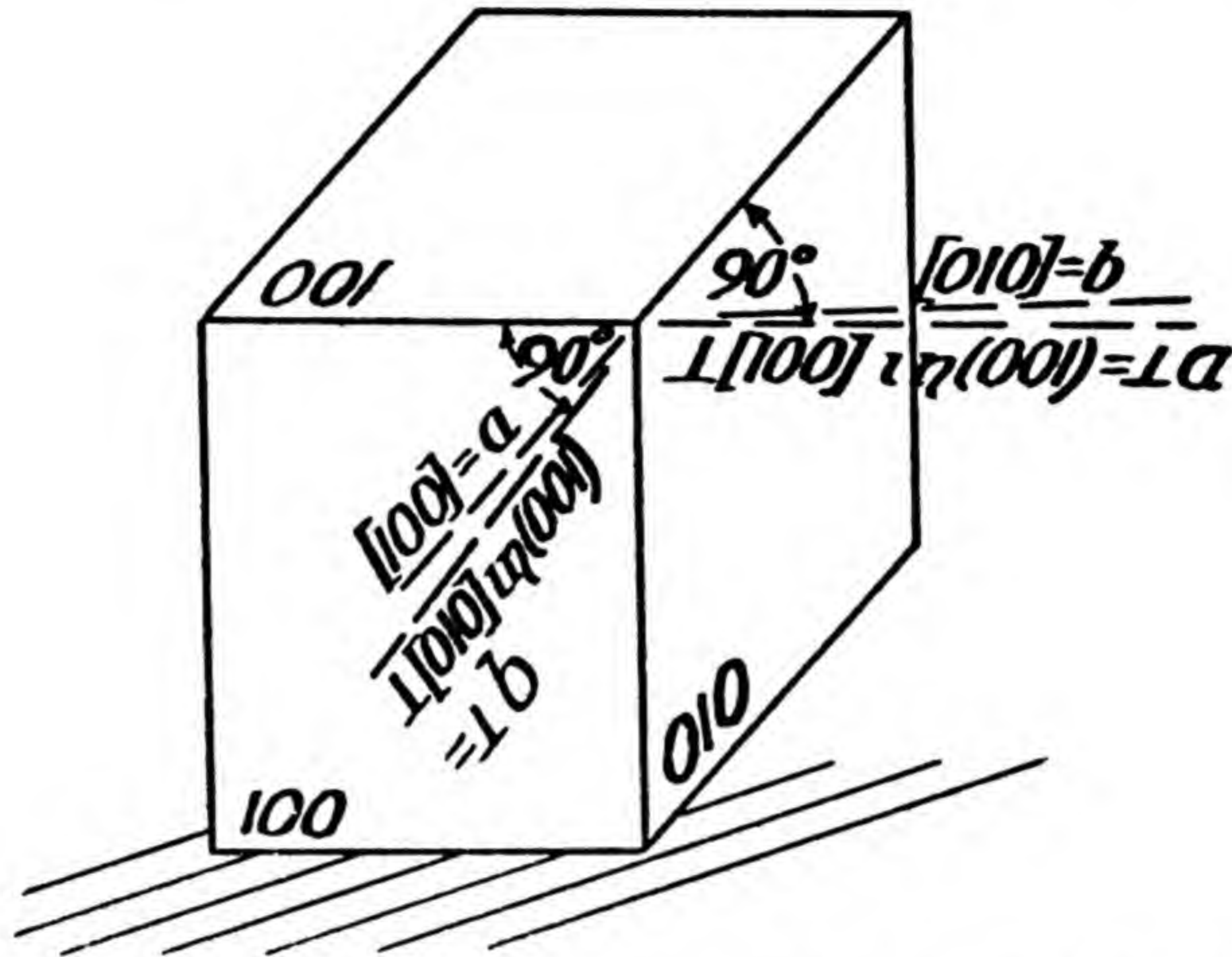
FIGURE 50.—*Parallel and complex twin laws having (001) as composition face*

These have twinning axes which at best are very close, as is shown here for sodic plagioclase. For other plagioclase crystals they quite coincide. Hence it is well not to recognize Manebach-Ala and Manebach-acline twinning except under special circumstances.

positions of the twin axes for Ala, acline, Manebach-Ala, and Manebach-acline twin laws. Since the angle γ ranges from 87° 1′ for albite to 91° 34′ for anorthite, the twin axes **b** and $\perp$ **a** virtually coincide and actually do coincide for one of the intermediate plagioclases. So also do the twin axes **a** and $\perp$ **b**. The maximum possible divergence for these axes is therefore 3° which is frequently within the limits of error of the technique. For the present at least a twin axis parallel or nearly parallel to the crystallographic axis **a**, is referred to the parallel law Ala; and a twin axis parallel or nearly parallel to the crystallographic axis **b** is referred to the parallel law acline if the composition face is (001) and not the rhombic section. Especially is this true for a simple twin. If, however, a multiple parallel twin is associated with a normal twin then theoretically some of the individuals are related according to a complex twin law.

Manebach and Carlsbad twinning is ordinarily simple; albite, acline, and pericline twinning are ordinarily multiple. Ala twinning may

consist of two individuals when it occurs alone but in combination with Manebach twinning is apt to be multiple. It is possible therefore to draw certain rapid conclusions on the microscope without requiring the stereographic projection, by using the outer east-west axis as already outlined to learn if the twins are normal or otherwise. A simple normal twin is Manebach, a multiple normal twin is albite, a simple parallel twin is Carlsbad, a simple normal twin associated with multiple parallel or complex lamellae is Manebach-Ala, and a simple parallel twin associated with multiple normal twinning is albite-Carlsbad complex twinning.

TABLE 10.—*The more important feldspar twin laws**

Normal twin laws—

Name	Designation	Composition face	Axis	Description
Albite	(010)	(010)	$\perp$ (010)	Usally multiple
Manebach	(001)	(001)	$\perp$ (001)	Usually simple
Baveno	(021)	(021)	$\perp$ (021)	Usually simple and
	(0$\bar{2}$1)	(0$\bar{2}$1)	$\perp$ (0$\bar{2}$1)	relatively uncommon

Parallel twin laws—

Carlsbad	[001] or c	(010)	c	Usually simple
Acline	[010] or b	(001)	b	
Pericline	[010] or b	Rhombic section	b	commonly multiple
Ala A	[100] or a	(001)	a	
Ala B	[100] or a	(010)	a	

Complex twin laws—

Albite-Carlsbad	$\perp$ [001] in (010) or $\perp$ c in (010)	(010)	$\perp$ c	" "
Albite-Ala	$\perp$ [100] in (010) or $\perp$ a in (010)	(010)	$\perp$ a	" "

* The simplification expressed in this table is not intended to deny the existence of the rarer twin laws of feldspar.

Table 10 gives the twin laws in condensed form following the nomenclature outlined. Certain theoretical or rare twin laws having (100) as composition face are omitted. Even if these possible twins are found they will be decidedly rare. Of those listed, albite, Carlsbad, and albite-Carlsbad complex twins are outstandingly the most common. Pericline, acline, and Manebach-acline are rather common in certain rocks having more calcic plagioclase. The composition face (001) tends to be found more commonly in rocks having calcic feldspar. Otherwise the composition of the rock seems not to be associated in any way with certain twin laws. This conclusion must be regarded as tentative. Coulson (1932a) suggests on the basis of a statistical study that the occurrence of the complex albite Ala B twin is favored in plagioclase of composition An_{30-35}.

Coulson studied the suggestion that different twin lamellae may have a different composition within one crystal aside from zonal

growth. When, in locating a twinning axis, he obtains a large triangle of error, he then rotates his projections to bring the pole of the composition face to the center, thereby revealing the symmetry of the twin. If the symmetry is not satisfactory he concludes that the lamellae differ in composition. He says (Coulson, 1932b):

"When it was found that the interpretation of the position of the crystallographic elements and the optical elements of the ellipsoids gave different compositions for the twinned individuals, another possibility was always examined during the study of the symmetry of the projection on (010) viz., that one of the twinned parts had not moved exactly 180° with reference to the other. If this latter method of interpretation was inapplicable, it was concluded that the twin actually was composed of individuals of different composition."

He apparently does not consider that strain in the crystal could account for such difficulties.

An excellent summary of our present knowledge of composition faces and their vicinal character is given by Manolescu (1934). Especially he calls attention to the growing agreement that the migration curves of the poles of composition faces are bands rather than lines.

Chapter 7
Rittmann Zone Method of Plagioclase Study

FEDOROW'S technique is the most widely used for feldspar study where feldspars are most extensively studied by the universal stage—namely in Europe and Asia—despite its serious limitations. The required graphical construction on a stereographic net is time consuming compared to the instrumental work which precedes it. This plotting is also so exacting that it is itself a source of error. Perhaps these facts account for the lack of adoption of this field of work to a greater extent by English-speaking petrographers, as the record of our literature shows. Especially tedious is the Fedorow method when the four-axis stage is used. The most serious limitation, however, is the difficulty of obtaining a satisfactory orientation of narrow twin lamellae. The walls of these lamellae overlap on inclination of the inner stage and confuse extinction. This difficulty prevails even in the more calcic plagioclase but is so frequent in the sodic plagioclases that commonly the twinned relationship of these narrow lamellae cannot be learned by the Fedorow technique.

The zone method developed by Rittmann (1929) overcomes some of these difficulties. It is designed primarily for rapid study and convenience, it functions especially well on narrow twin lamellae, and it requires no graphical construction. The inner east-west axis of the five-axis stage is not used. It is not however, so reliable as the Fedorow technique and it cannot be used well on plagioclase of 60 per cent or more anorthite and not at all on plagioclase of 70 per cent or more anorthite unless the composition face is known. It is invaluable for use with the Fedorow technique, especially when many twins are to be studied. As indicated, it functions best where the Fedorow method is weakest, and the Fedorow method functions best where the Rittmann method fails. The two methods are therefore complementary. Rittmann's method is customarily known as the zone method, the name he gave to it.

The principle of the zone method is the same as that which underlies the determination of feldspars in oriented sections. An unknown plagioclase is oriented, not optically but crystallographically to one of several suitable positions, and extinction angles are measured. These values of extinction are applied on curves which give the composition. The relative extinctions of adjacent lamellae give information that leads to the recognition of the twin laws.

The most readily obtained, significant orientations for this purpose
are those in which one composition face is parallel to a cross hair and
to the axis of the microscope. Therefore the crystal must be twinned
in order to learn its composition. If a crystal, so oriented, is rotated
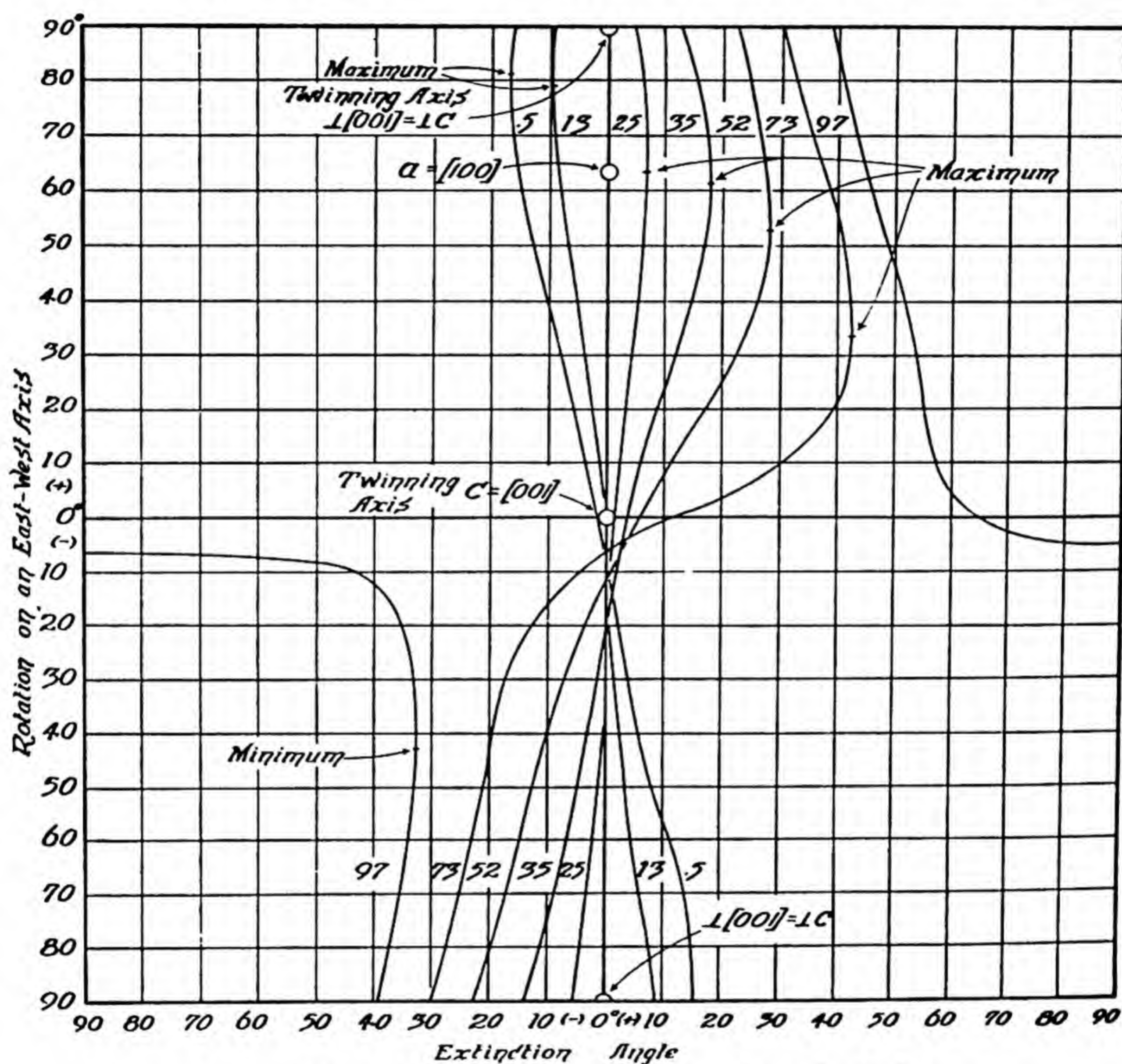
FIGURE 51.—*Extinction angle curves for plagioclase*

In a section in which the composition face (010) is vertical. If the composition
face is made north-south and the crystal is rotated on an east-west axis extinction
may be measured for several settings on the east-west axis, and a part of the
curve constructed. The directions c, the Carlsbad twinning axis. ⊥ c, the albite
Carlsbad complex twinning axis, and ■ the Ala twinning axis (also the cleavage
(001) is vertical) serve as reference positions. The ordinates are readings on the
east-west axis of rotation. The abscissae are extinction angles measured from
(010) to a'.

on an axis perpendicular to the composition face, the composition face
remains vertical. The extinction angle changes however with this
rotation, the amount of change depending upon the composition.
The change may be plotted as a curve for different positions of rota-
tion and for one composition. Figures 51 and 52 show several such
curves. The abscissa represents extinction angles, the ordinate rep-
resents rotation on the chosen universal-stage axis.

It is unnecessary, however, to measure the entire curve of an un-known since any one of several points on the curve in a known direction is adequate.

The three common composition faces cannot always be dis-
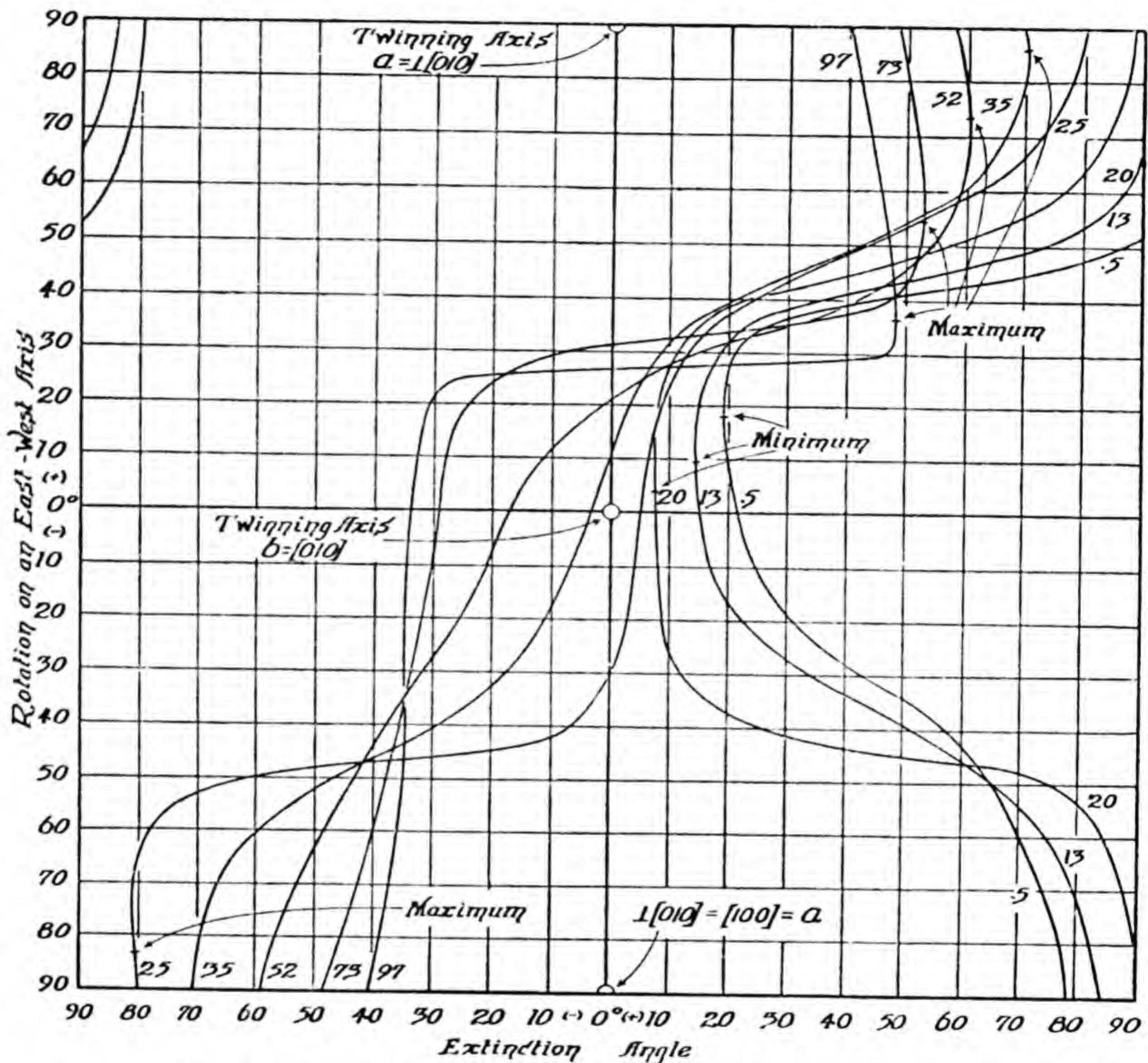
FIGURE 52.—*Extinction angle curves for plagioclase*

For orientation in which the composition face (001) is vertical. Ordinates are rotation readings on the east-west axis. Abscissae are extinction angles measured from (001) to a'.

tinguished at a glance, as can the Baveno composition face. They are the side pinacoid (010), the basal pinacoid (001), and the rhombic section which is the composition face of the pericline twin law. The extinction-angle curves are not the same for these different composition faces, and it is necessary to learn therefore which one has been chosen. This is done by learning whether the fast ray (α') is alone parallel to the composition face or whether both fast and slow rays fall in this position, as illustrated in Figures 53-56. The simplest of these is Figure 54, in which the optic plane is nearly parallel to (001).

Suppose (010) is the composition face and the axis of rotation is perpendicular to it. Then γ remains nearly parallel to the axis of rotation, while α and β (both faster) are perpendicular to it. This is recorded as a positive zone axis—so determined by an accessory plate
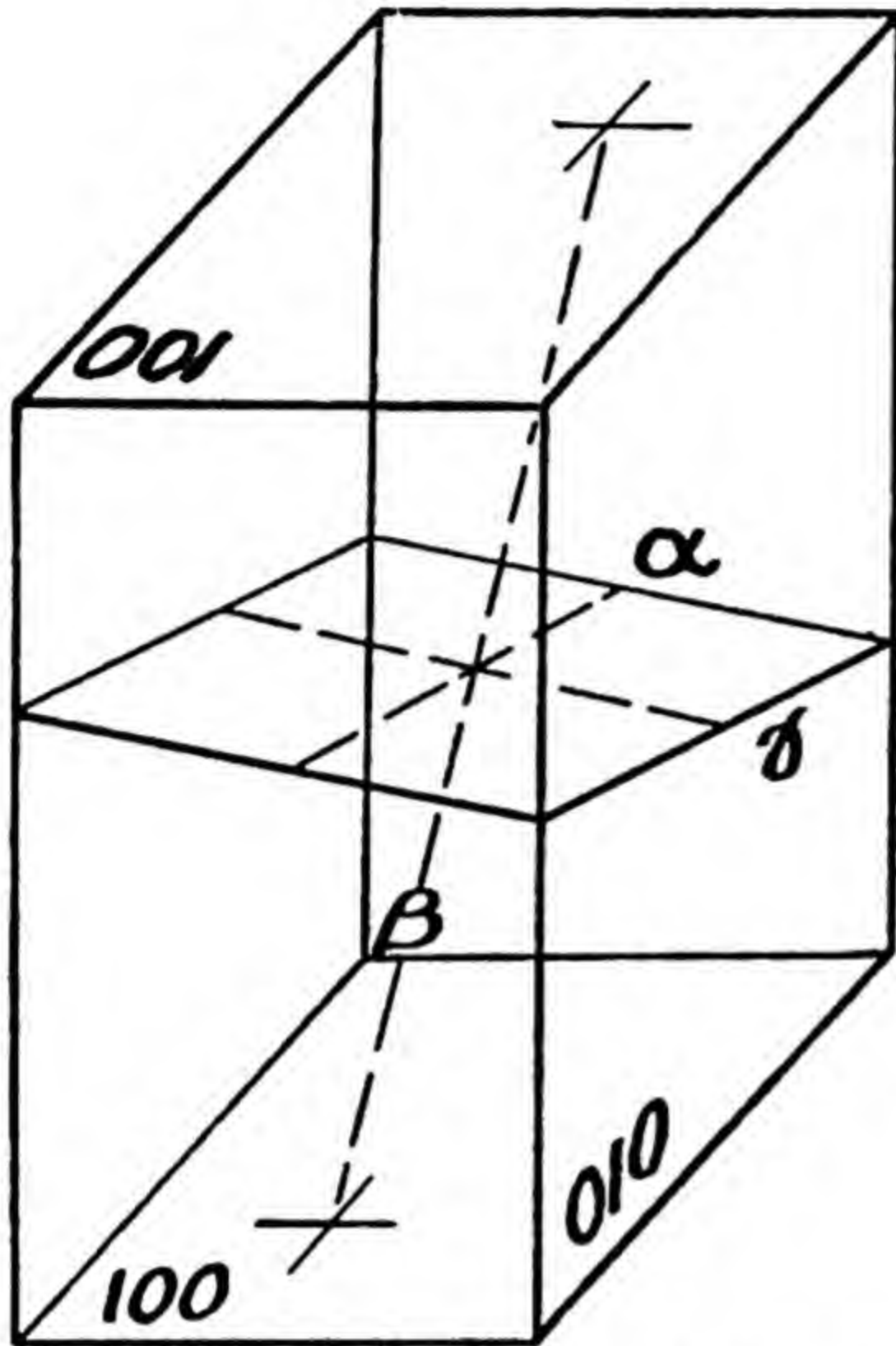
FIGURE 53.—*Optical orientation of albite*

Showing the optic plane roughly parallel to (001).
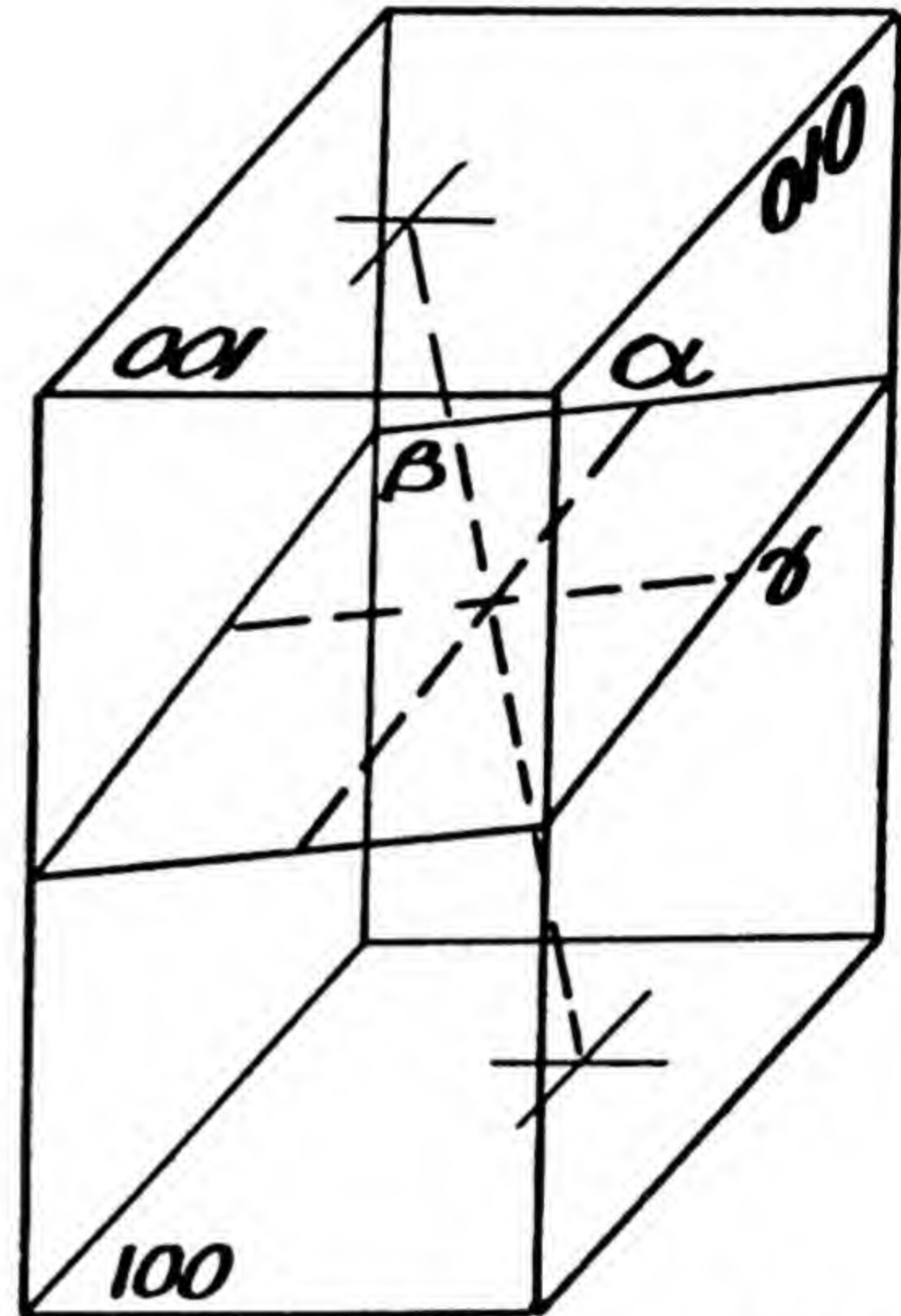
FIGURE 54.—*Optical orientation of oligoclase*

Showing the optic plane roughly parallel to (001).

as described below. If (001) is the composition face and the axis of rotation is perpendicular to it, then β remains nearly parallel to the axis of rotation, and α or γ may be perpendicular to it. This is recorded as a variable zone axis since fast and slow rays alternate. This latter condition holds, too, for the rhombic section. For the more calcic plagioclases, however, this method fails, as Figure 57 illustrates, since the optic plane is unfavorably oriented.

In detail the procedure to determine the composition of a plagioclase is as follows. With all axes at their proper zero positions orient the chosen composition face north-south by a rotation on the inner vertical axis, and make it vertical by a rotation on the north-south axis. As for the Fedorow method, it is not always easy to attain accuracy in making the chosen face vertical. Test the orientation of the composition face by rotating on the outer east-west axis if a low-power objective is used. Some prefer to use a higher-power objective (20×) to reach the vertical position.

The optical character of the zone axis is determined next. Rotate on the microscope stage 45° in the direction which makes the outer east-west axis parallel to the slow ray of the accessory plates. Insert the first-order red plate and rotate on the outer east-west axis. As
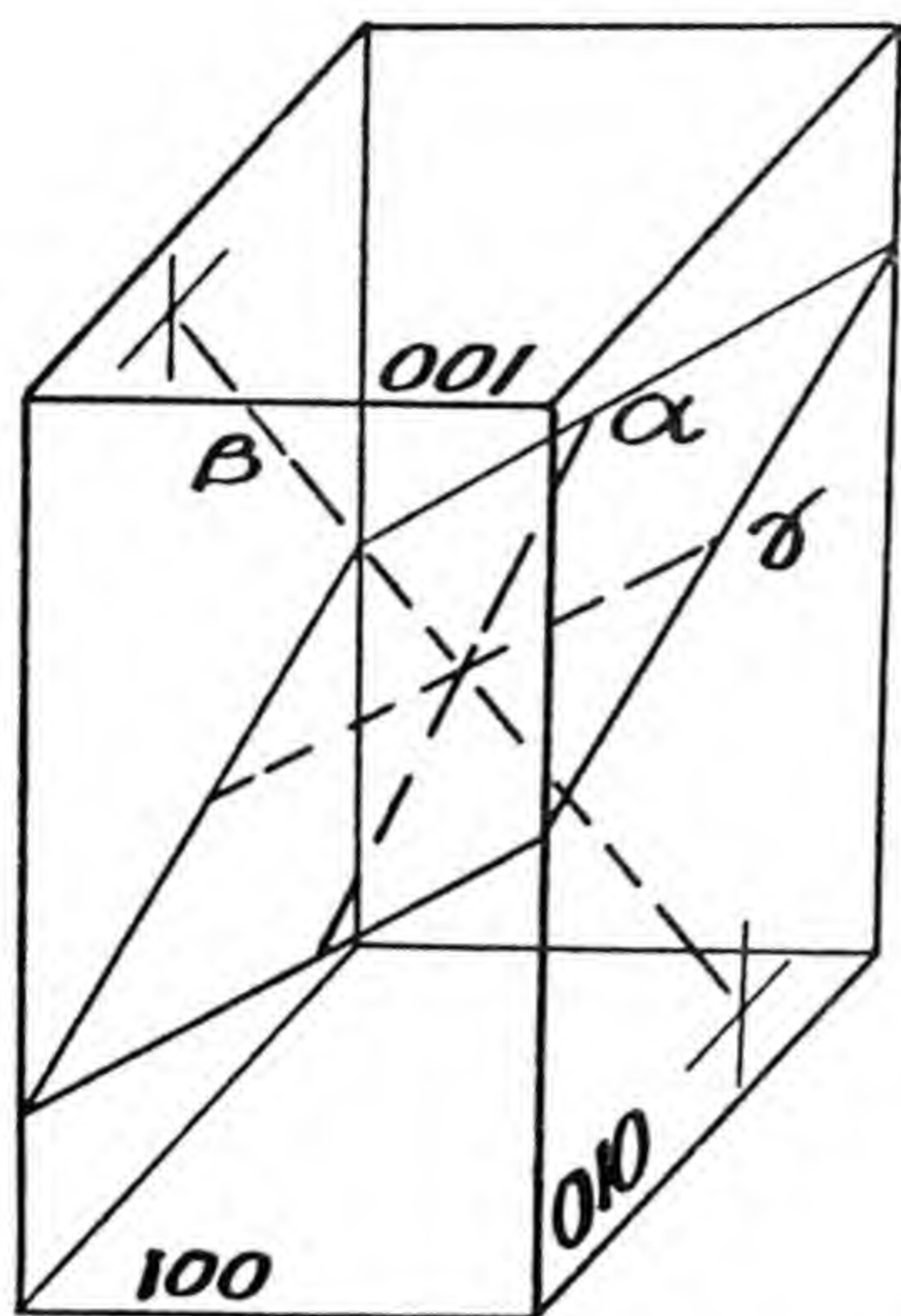
FIGURE 55.—*Optical orientation of andesine*
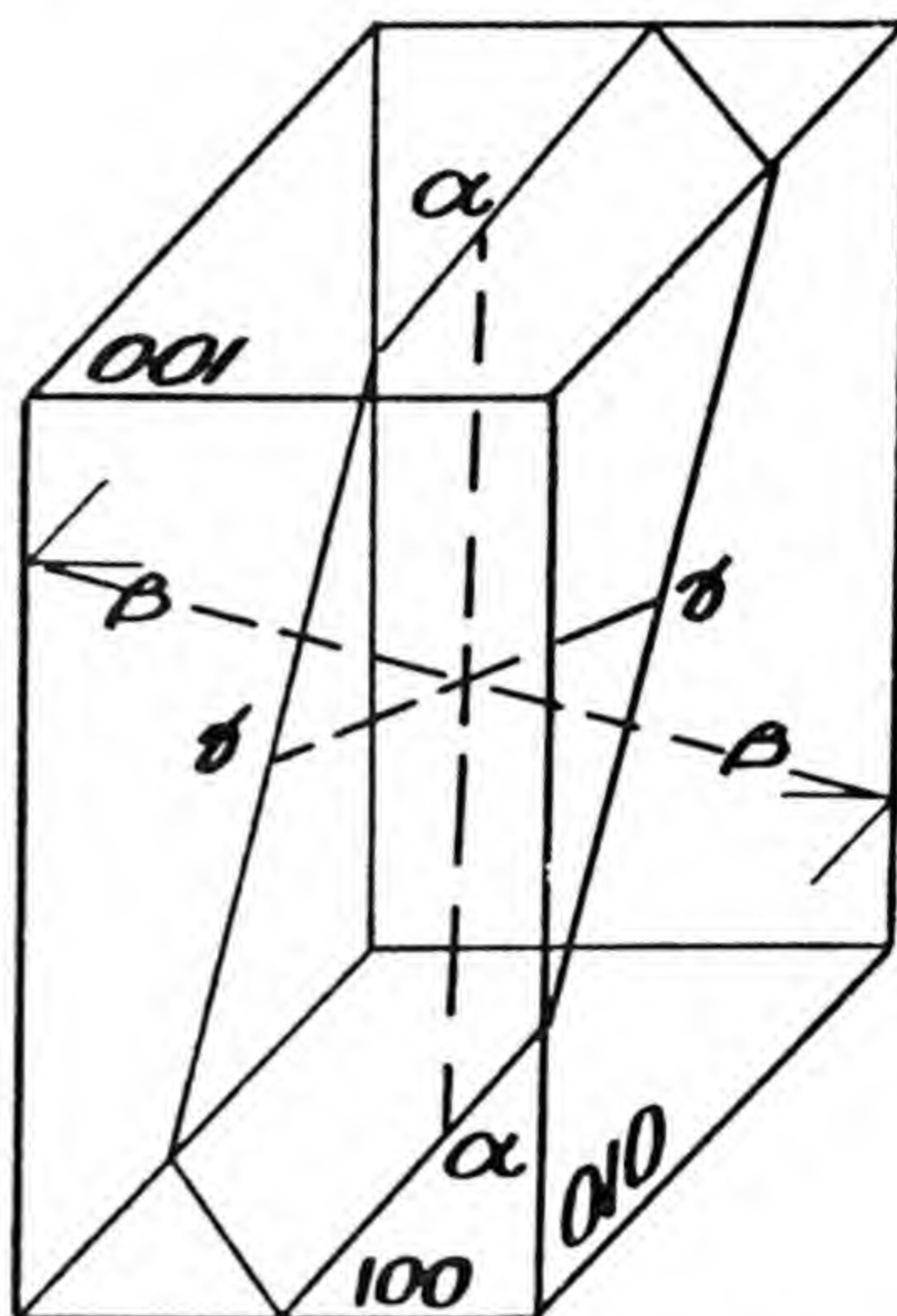
FIGURE 56.—*Optical orientation of labradorite*

already explained there are two possibilities: (1) If the colors rise to the second order, reaching even the second order red in some positions, the composition face is (010); that is, the zone axis is positive. (2) If the colors both rise and fall on rotation of the outer east-west axis the composition face is either (001) or the rhombic section; that is, the zone axis is variable. Irregular results usually indicate a very calcic plagioclase, for which the method fails.

Knowing now the composition face, return the microscope stage to its zero position and rotate on the outer east-west axis to find another recognizable direction within the face. This will be an intersecting cleavage, or another composition face at nearly 90° to the first, a position of maximum extinction or a twin axis. If it is a cleavage or composition face, make it vertical by the same criteria used for the north-south composition face. The twin axis will be discussed later. The twin unit in which this cleavage or composition face is made vertical is designated unit one. The extinction angle of this unit is to be distinguished later from that of other units.

A known direction in a known composition face is now parallel to the axis of the microscope. Extinction angles in such an orientation are of critical value for determining the composition of the crystal. Measure the extinction angle from α' to the north-south composition
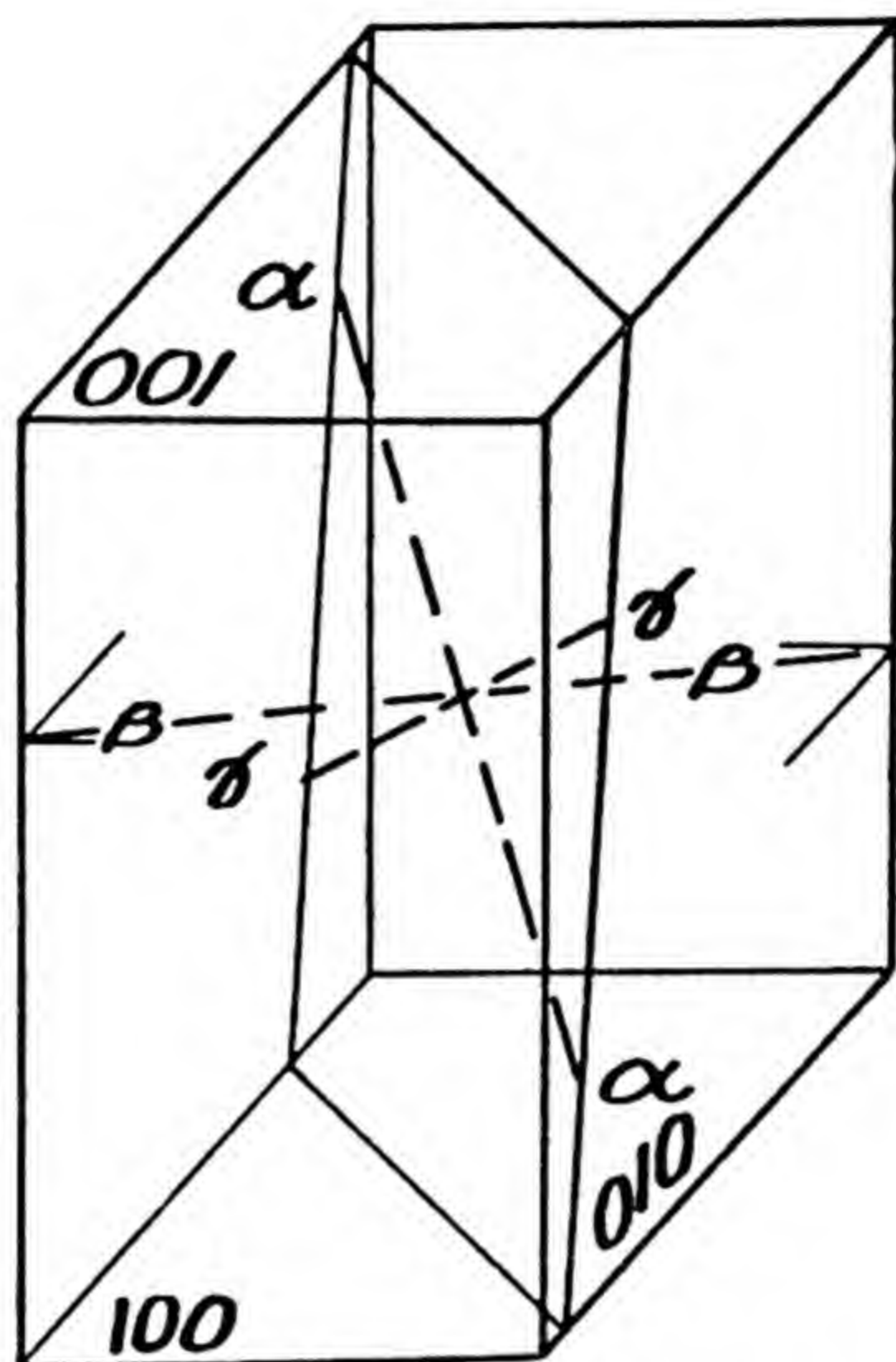
FIGURE 57.—*Optical orientation of bytownite*

face in unit one. If the angle is less than 15° it may be either positive or negative according to the customary rule — namely, if α' falls in the acute angle between the chosen crystallographic planes (cleavage or composition faces) the sign is (+), if in the obtuse angle the sign is (—). These crystallographic planes (001) and (010) intersect in the established orientation at about 86°.

Assume that the north-south composition face is (010). On rotation about the outer east-west axis transverse twin lamellae appear and are made vertical. Although these lamellae are probably the rather common pericline twin lamellae they may be acline or Ala lamellae. (Seldom need pericline lamellae be confused with Manebach twinning which is morphologically similar to Carlsbad twinning.) If the lamellae are acline or Ala twins it may be possible to see some indication of cleavage parallel to them by removing the analyzer and closing the substage diaphragm. If no parallel cleavage is found assume the lamellae to be of the pericline type. Measure the extinction angle to α' and apply this value on Figure 58 to the curve marked

pericline ("Per"). In any case the curves "Per" and a approximately agree for the sodic plagioclase up to An_{70}.

If on the other hand the search for cleavage on removal of the analyzer revealed some parallel to the transverse twin lamellae, or if
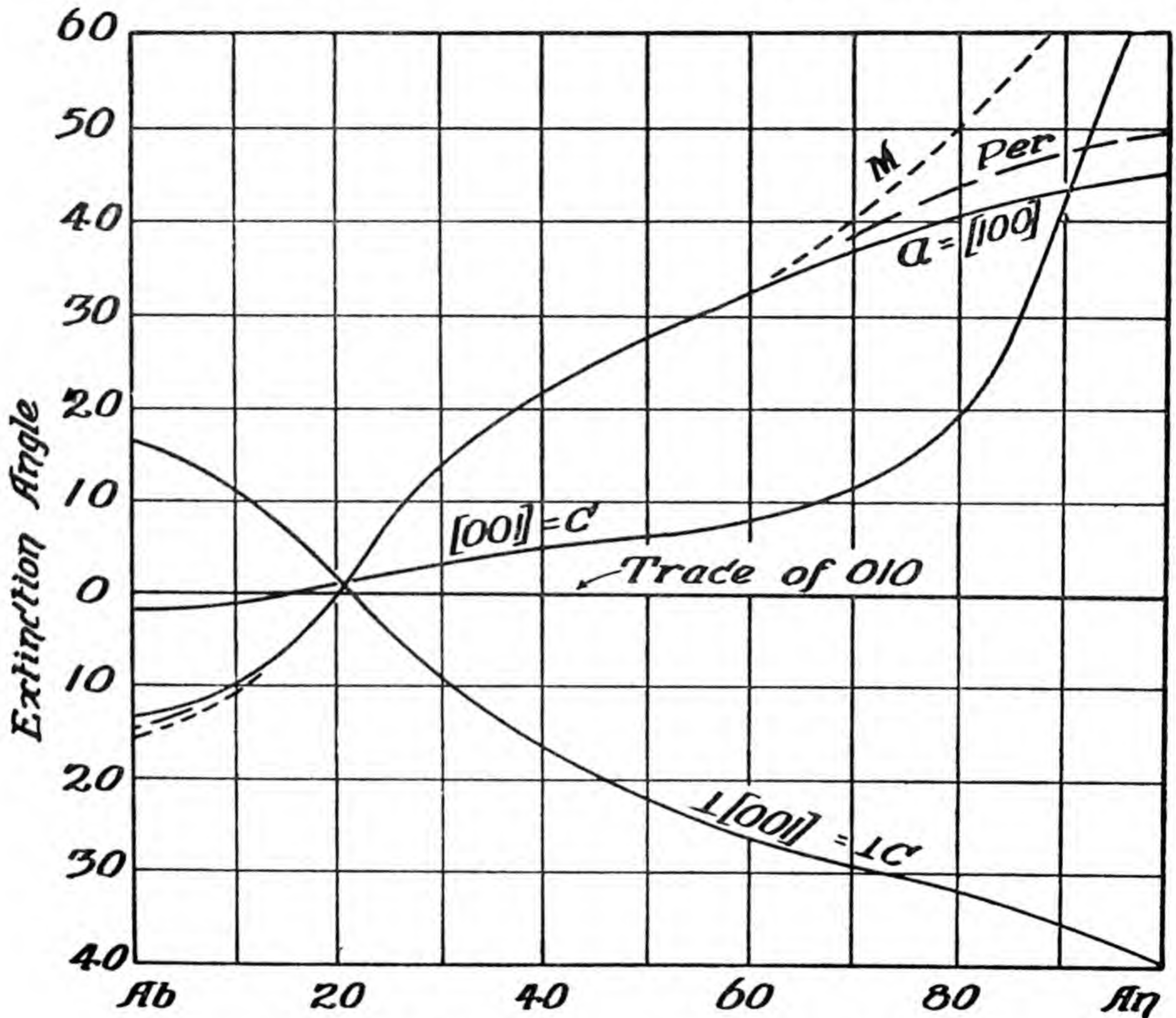
FIGURE 58.—*Extinction angle curves for plagioclase*

When (010) is vertical. Curves are given for five directions in (010): the maximum extinction angle, the intersection with the pericline lamellae, the a axis, and the twinning axes c and ⊥ c. Ordinates are the extinction angle measured to a'; the abscissae are the anorthite content.

no tranverse twinning is available and a direct search is made for cleavage, then this is made vertical as was done for the pericline composition face. As before, the extinction angle is measured, and the value used on Figure 58, but the curve a is chosen instead. When the basal cleavage (001) is made vertical the crystallographic axis a is parallel to the axis of the microscope since (010) is already vertical.

Occasionally neither the pericline composition face nor the crystallo-

graphic direction **a** is available. The remaining curve on **Figure 58** may then be used—the curve for the maximum extinction angle. This angle is found by rotating on the outer east-west axis in small increments (10°) and measuring the extinction angle for each setting. This angle will be found to increase to a maximum (the desired value)
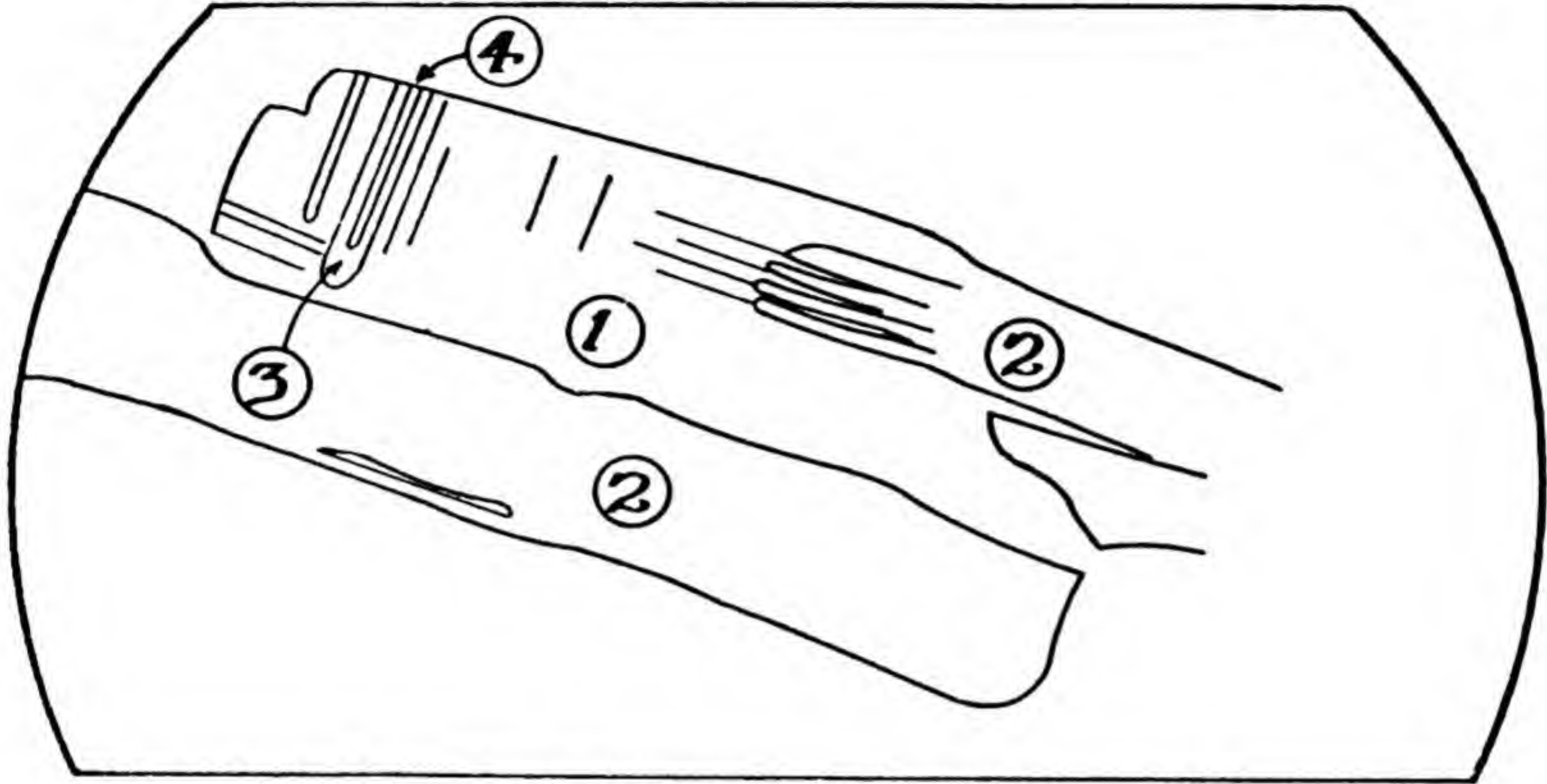
FIGURE 59.—*Key to Figure 4 of Plate 7*

and then diminish. Use this maximum value on the curve designated M.

Some examples follow:

1. (Fig. 59; Pl. 7, fig. 4). The composition face between units 1 and 2 was first made vertical and north-south by adjusting the inner vertical and north-south axes. Neither is recorded, necessarily, since the values will not be used. However, the north-south axis rests at 5°E. It is not known yet which composition face this is.

The crystal was next turned 45° on the microscope stage to make the outer east-west axis parallel to the slow ray of the accessory plate, *i. e.,* counter clockwise on the instrument used. After inserting the gypsum plate the crystal was rotated widely on the outer east-west axis, and the color change observed. Blues and greens predominated, indicating that the composition face is (010).

The stage was returned to its zero position, the gypsum plate removed, and a search made, by rotating on the outer east-west axis, for another intersecting composition face or cleavage. At 15°N cleavage was found in unit one making an angle near 90°. This could be only the cleavage (001). Therefore **a** is parallel to the axis of the microscope.

Continuing the observation on unit one (so designated in an ordinary case because the intersecting cleavage or other datum plane was discovered in it) the extinction angle was measured from the composition face to α'. It was recorded as 84° and is designated E_1. This value is now used on the curve **a** of Figure 58 to learn the anorthite content of the crystal—it is An_{84}.

2. Figure 5 of Plate 7 illustrates a common twin combination found in gabbroic rocks. Unit one (Fig. 60) was studied first. Composition face 1-2 was made

vertical at 28°W. Composition face 1-3 was made vertical at 40°N. The composition face 1-2 has a positive zone axis revealing it to be (010). The extinction angle of unit 1 in this oriented position is 31° which by Figure 58 shows a composition of An_{59}.

8. This crystal illustrated in Figure 3 of Plate 5 and in Figure 61, differs in that when the composition face 1-2 is vertical and north-south it shows no intersecting
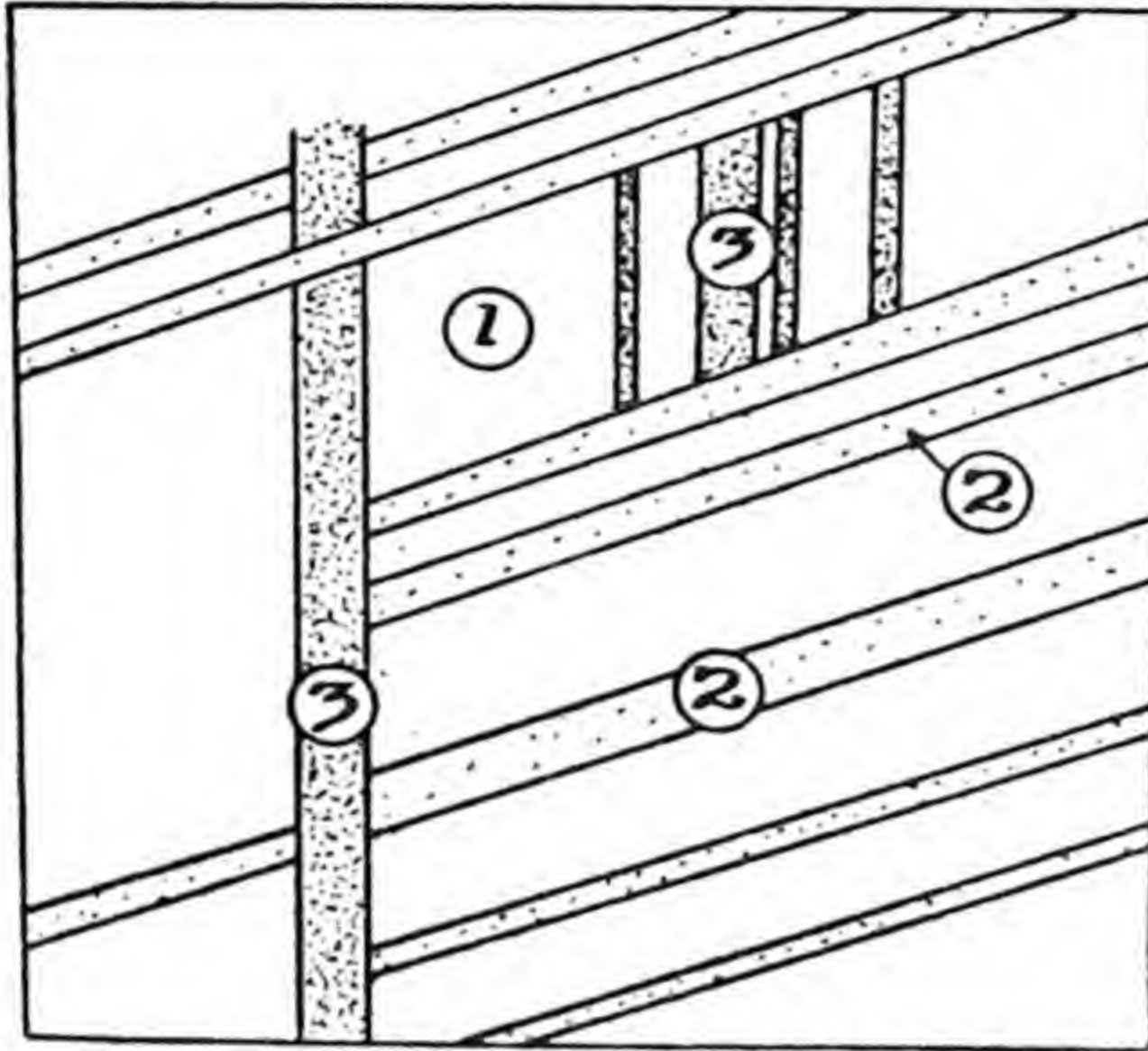
FIGURE 60.—*Key to Figure 5 of Plate 7*
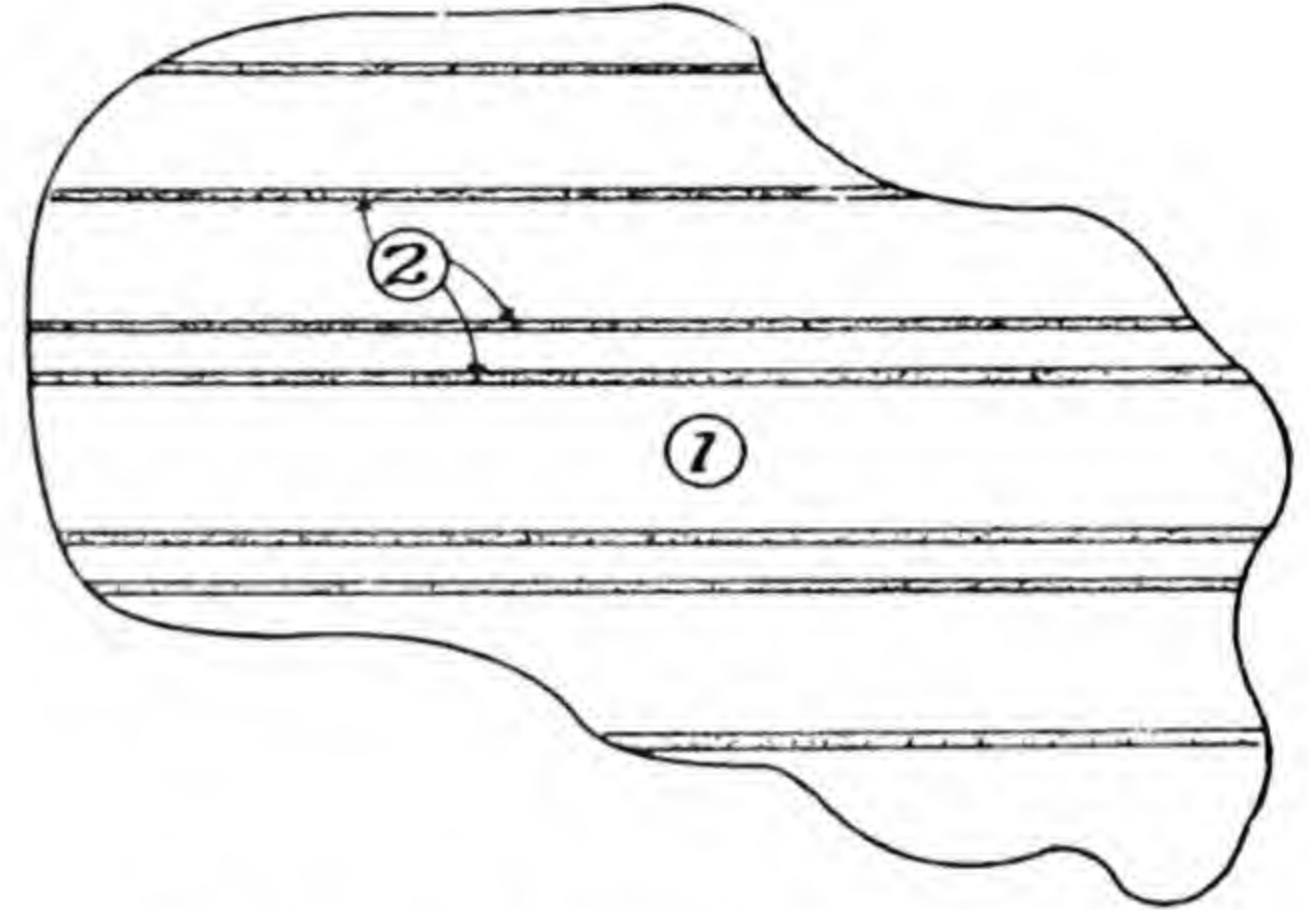
FIGURE 61.—*Key to Figure 3 of Plate 5*

lamellae, or cleavage. The zone axis is positive. Further, the position of maximum extinction is not available since the slide would need to be turned almost on edge to reach it. To learn the composition of the crystal, the method of determining the extinction curve is used, although this is a somewhat slower procedure. The outer east-west axis was set as shown in tabular form below, at 10° intervals, and the extinction angle was measured for each setting. (Clockwise extinction is designated (+).)

O.E.W₁	0°	10°N	20°N	30°N	40°N	50°N	60°N	65°N	10°S	20°S	30°S	40°S	50°S	60°S	65°S
Ext.	0°	—1	—2	—3.5	—6	—8.5	—11	—12	+1	+3	+4.5	+6	+8	+10	+10°+

(It is merely coincidence that 0° on the outer east-west axis yields 0° extinction.)

These data are best converted to a curve on graph paper as shown in Figure 62. This curve is then compared with the curves of Figure 51. It should compare with one of them or with a reasonable interpolation to indicate the composition. In this case it indicates An_{32}.

Assume next that the north-south oriented composition face is (001) or the rhombic section as indicated by the optical character of the zone axis. These conditions are somewhat less satisfactory and more difficult to use than the orientation of the plane (010). There may be doubt about the identity of the composition face, and it should be known whether it is (001) or the rhombic section. Remove the

analyzer, stop down the substage diaphragm, and search for the cleavage which is parallel or nearly so to the composition face. Make the cleavage vertical and compare the reading on the north-south axis with that for the oriented composition face. If the cleavage is
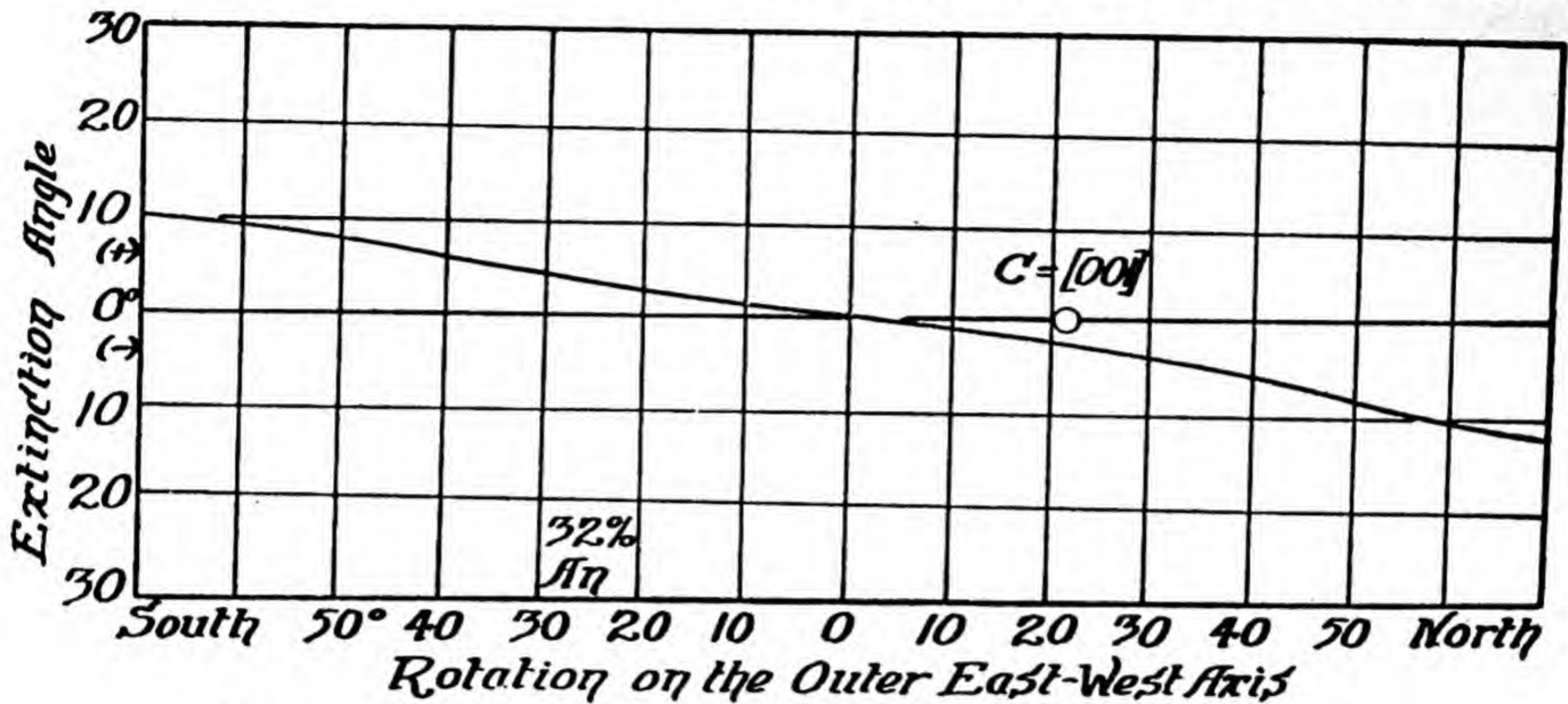
FIGURE 62.—*Extinction angle curve for Figure 3 of Plate 5*

This curve is to be compared with the curves of Figure 51 to learn the composition of the crystal.

parallel to the composition face the plane is definitely (001). If the cleavage is inclined the composition face must be the rhombic section,

EXPLANATION OF PLATE 6

FIGURE

1. View of the crystal of Figure 3 of Plate 7, after the composition face has been made vertical but before a rotation has been made on the outer east-west axis to locate the twinning axis. Note the contrasting birefringence colors of the Carlsbad lamellae. The slide is inclined in the photograph, hence only the center is in focus. (×47) *See* Figure 73.

2. The same field as that of Figure 1, but rotated on the outer east-west axis to make the Carlsbad twinning axis either vertical or horizontal. Note equal illumination of the Carlsbad lamellae.

3. Crystal of diopside showing properly centered compensation shadow obtained by means of the Berek compensator. (×15)

4. Same crystal of diopside, not quite at the 45-degree position and showing the compensation shadow of the Berek compensator off center. In a small crystal this could be interpreted as no compensation.

5. Same crystal as that of Figure 3 of Plate 7, but more highly magnified. This is the first of a series of three photomicrographs to show how a composition face is made vertical. The reference plane is the composition face of the Carlsbad twin. The slide was parallel to the microscope stage when photographed—the entire field is in focus. (×400)

6. Same field as that of Figure 5 but partly inclined as the first step to make the face vertical. (×400)

7. Same field as that of Figures 5 and 6 but fully inclined to make the Carlsbad composition face vertical. Note how sharp is its trace. Note too that the sides of the field are out of focus on account of the inclination. (×400)

FIGURE 1

FIGURE 2
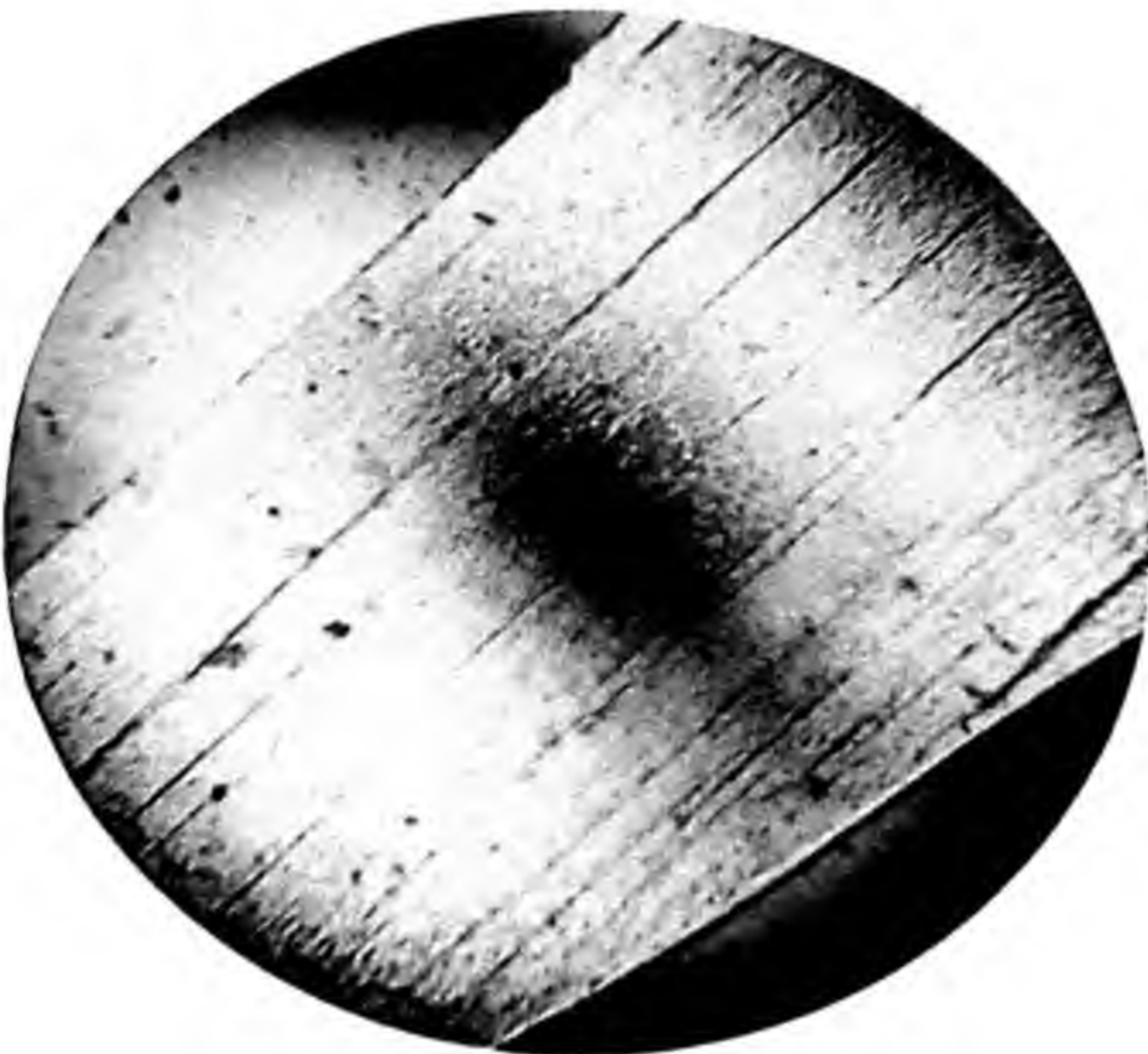
FIGURE 3
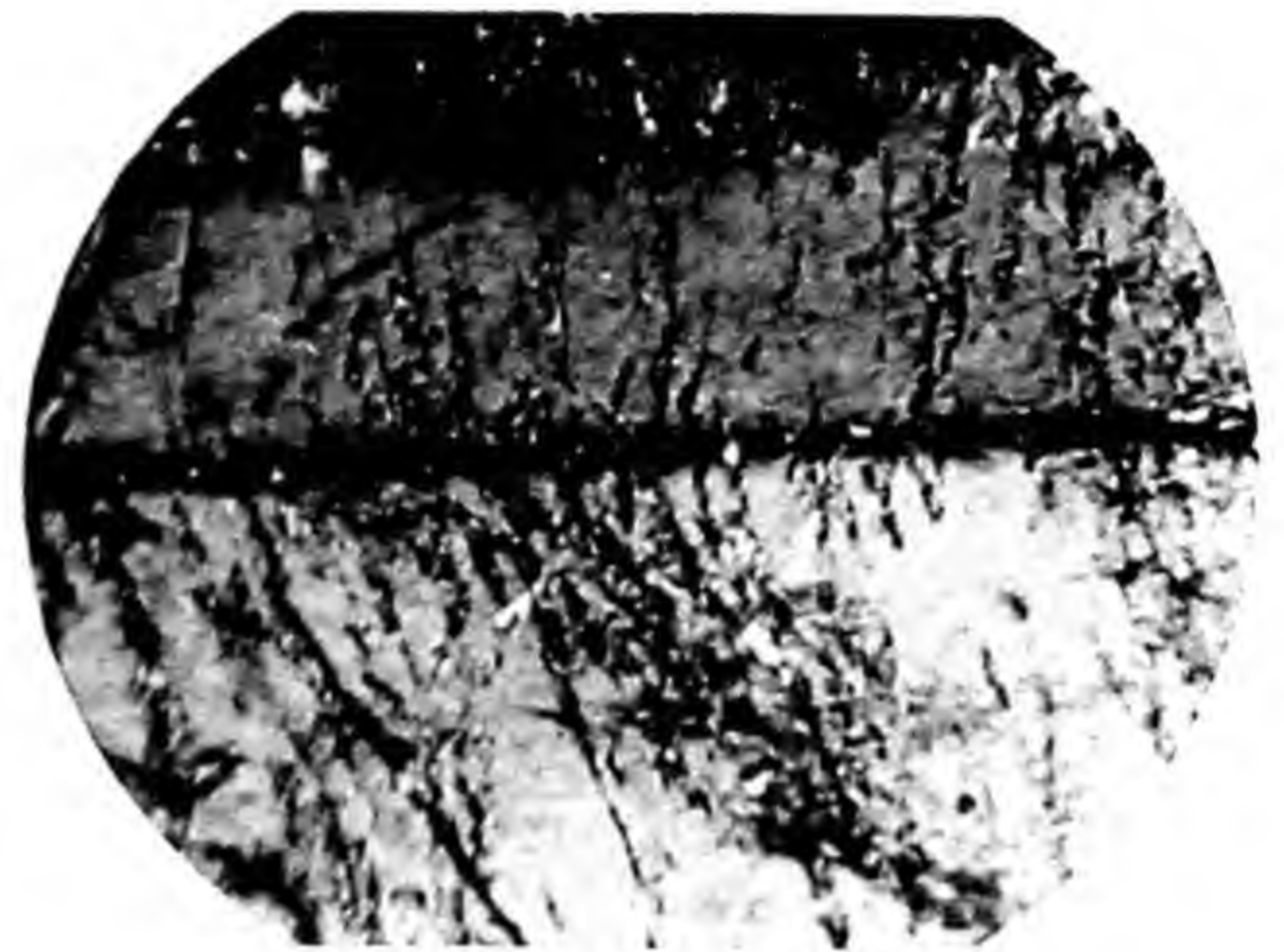
FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

SOME OPTICAL EFFECTS ON CRYSTALS
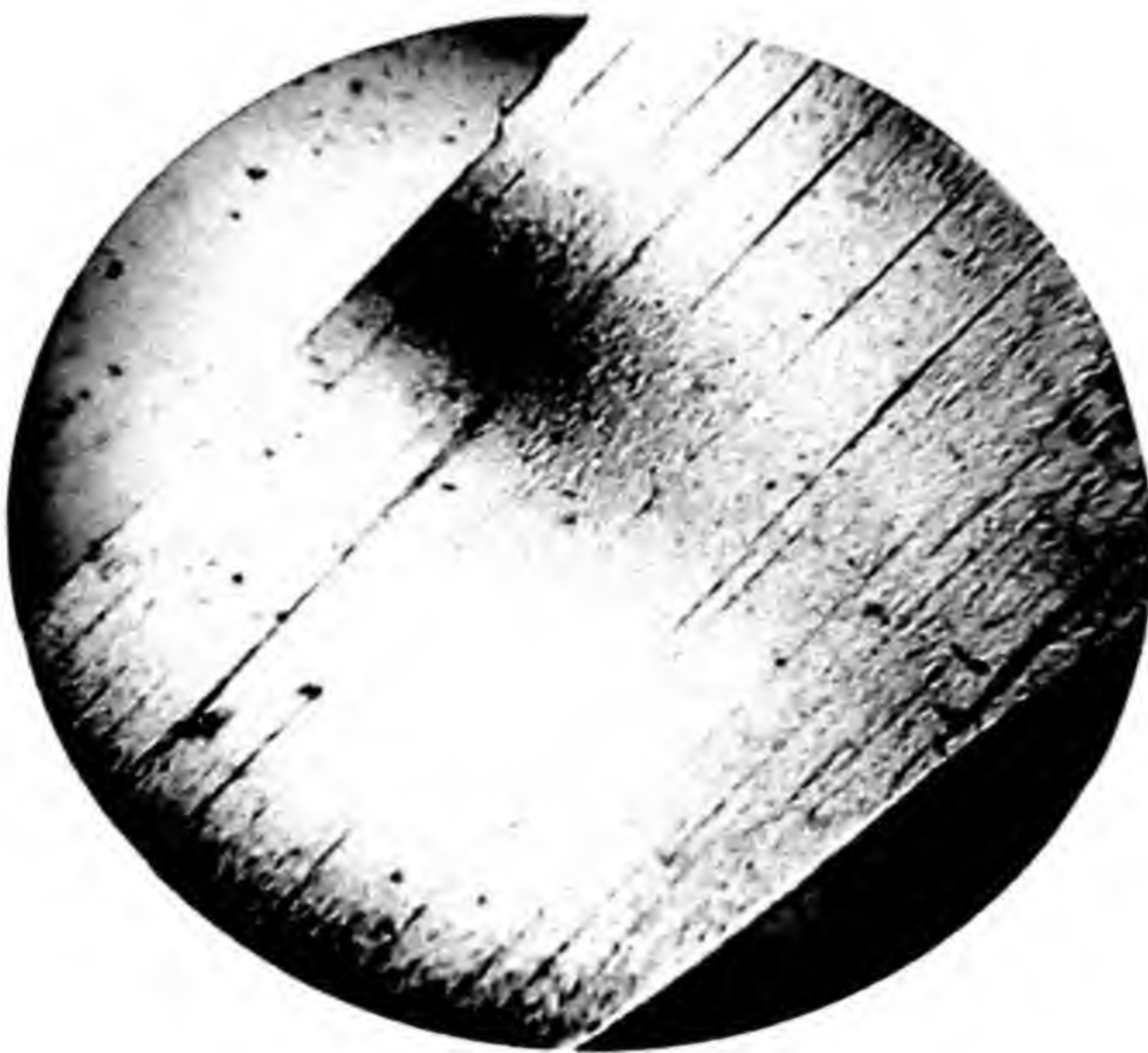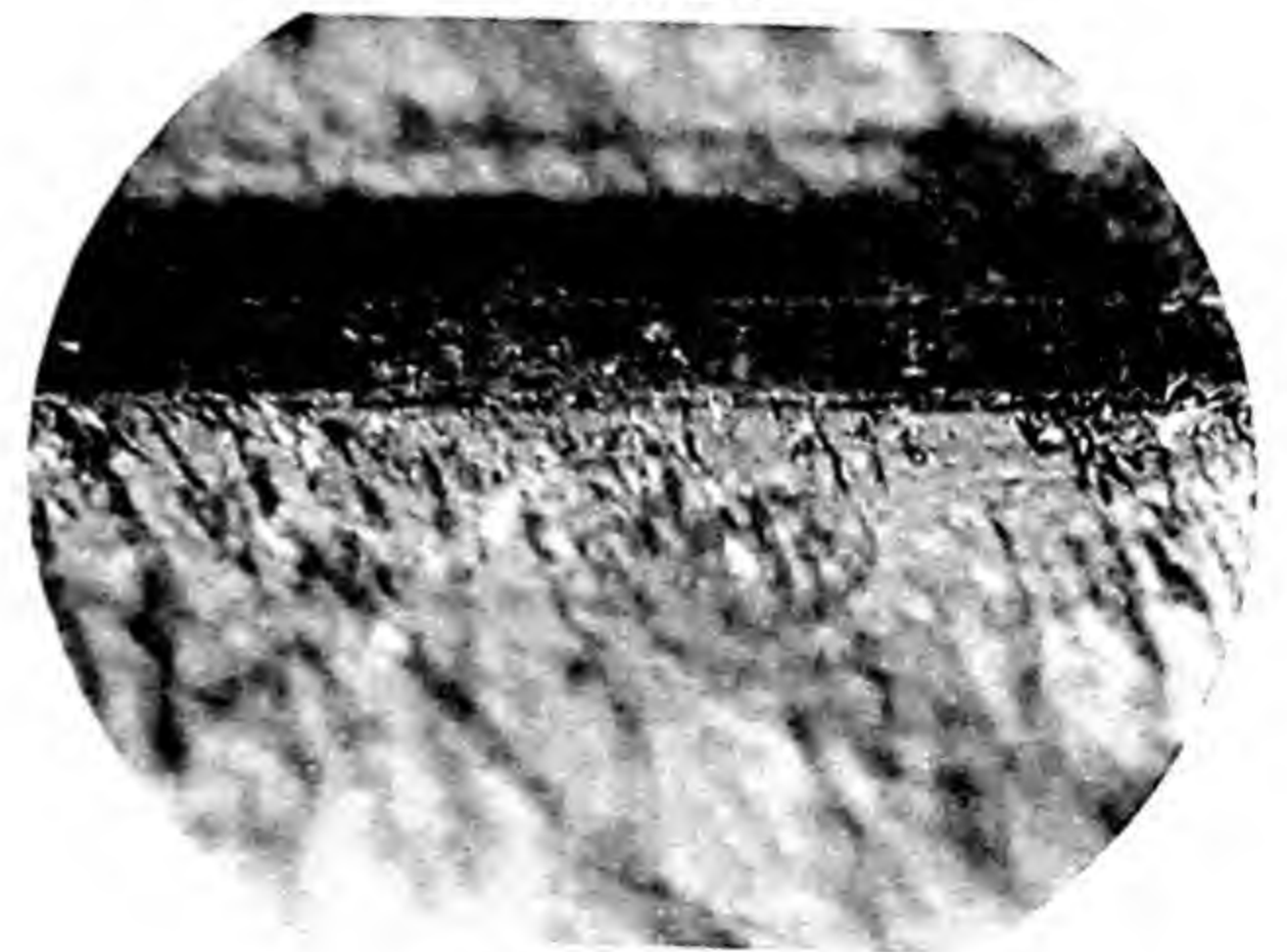
Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

CRYSTALS STUDIED IN DETAIL IN TEXT

and the twin law is pericline. If the angle between the cleavage and the rhombic section can be determined this will serve as an indication of the composition of the plagioclase, useful mainly for confirmation of the subsequent determination.

In theory this procedure is simple, but in practice, with one exception, the pericline composition face is difficult to identify unless an orientation procedure is followed through. If the crystal can be oriented to make **b** parallel to the axis of the microscope the angle made by the composition face and the (001) cleavage is almost the true angle and can usually be seen even though small (Fig. 67; Pl. 5, fig. 1). This position, **b**, can be recognized most easily by the equal illumination of the adjacent twin lamellae in the parallel and 45-degree positions with respect to the nicols, since it is a twinning axis.

Assuming the pericline composition face to remain vertical but to be rotated on an axis normal to it, as the angle between the axis of the microscope and **b** increases the (001) cleavage and the trace of the composition face become more nearly parallel until the axis of the microscope is perpendicular to **b**. This position also is most easily recognized, as was **b**, by the equal illumination of adjacent twin lamellae. As the 90-degree rotation is made, the relationship of the cleavage to the composition face ordinarily becomes progressively more obscure, especially if the angle between (001) and the rhombic section is small—that is, if the composition is at all near andesine. In the **b** position the twin law and the approximate composition are

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EXPLANATION OF PLATE 7

FIGURE

1. Cyanite crystal recorded in Table 24, showing the two cleavages and the composition face of the twin. (×47)
2. Plagioclase crystal from the north branch of the Wolf River, Wis. (×200) *See* Figure 71.
3. Plagioclase crystal from near Dunbar, Marinette County, Wis. (×64) *See* Figure 73.
4. Plagioclase crystal from Duluth gabbro, on highway at Birch Lake, Superior National Forest, Minn. (×47) *See* Figure 59.
5. Plagioclase crystal from Duluth gabbro, near Loon Lake, Cook County, Minn. (×47) *See* Figure 60.
6. Plagioclase crystal from gabbro quarry 1 mile north of Mellen, Wis. (×47) *See* Figure 83.
7. Heavy residual grain mount showing hornblende with balsam filled cleavage cracks. (×64)
8. Same hornblende grain as in Figure 7, but the plane of the cleavage cracks makes a greater angle with the axis of the microscope so that the incident ray impinges on the balsam film within the critical angle and is therefore transmitted, causing the cleavage cracks to appear light.

evident from the angle made by the cleavage with the composition
face, and no other method is needed. In the ⊥**b** position the
cleavage may or may not be suitable for study. If it is not suitable,
the procedure should be to orient one unit and the composition face
and construct a stereogram. (*See* Chapters 8 and 9.)
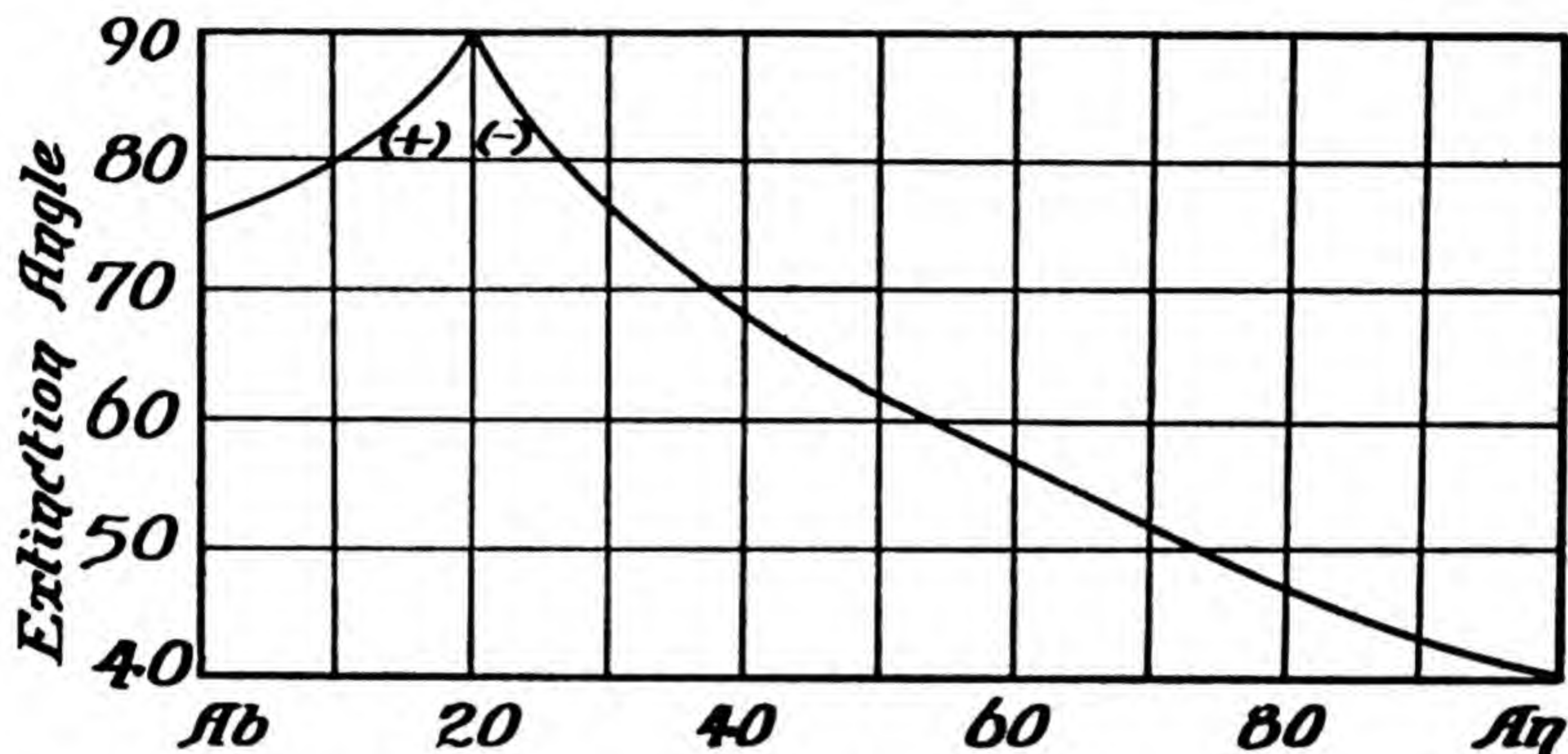
FIGURE 63.—*Extinction angle curve for plagioclase measured to the
pericline lamellae*

If conditions are favorable and the composition face is recognized as
the rhombic section by reference to the cleavage then on rotation
of the outer east-west axis there is only one reference direction—
namely, the intersection with the crystallographic plane (010) as
represented by transverse cleavage or twin lamellae. This direction
is, of course, the same as the intersection of the pericline lamellae
found in the zone ⊥ (010). The extinction-angle curve of Figure 58
may, therefore, be used now by measuring extinction from α' to the
(010) cleavage. For convenience, however, since the operator ordi-
narily measures these extinction angles from the north-south reference
plane rather than the east-west plane, Figure 63 is offered. This gives
the extinction angle from the trace of the vertical pericline composi-
tion face to α'. Parenthetically, in case of error in distinguishing
(001) and the rhombic section, observe the similarity between Figure
63 and **a** of Figure 64.

Suppose that the composition face is (001). As was done for the
plane (010), rotate on the outer east-west axis to find either the
other cleavage (010) or other twin lamellae which have (010) as
composition face. These lamellae should cut the oriented plane at
nearly 86°. If such are found, make them vertical. Then the crystal-
lographic axis **a** is parallel to the axis of the microscope, and the

extinction angles for the position are critical. For uniformity measure the extinction to α' and refer the value to Figure 64 using the curve **a**.
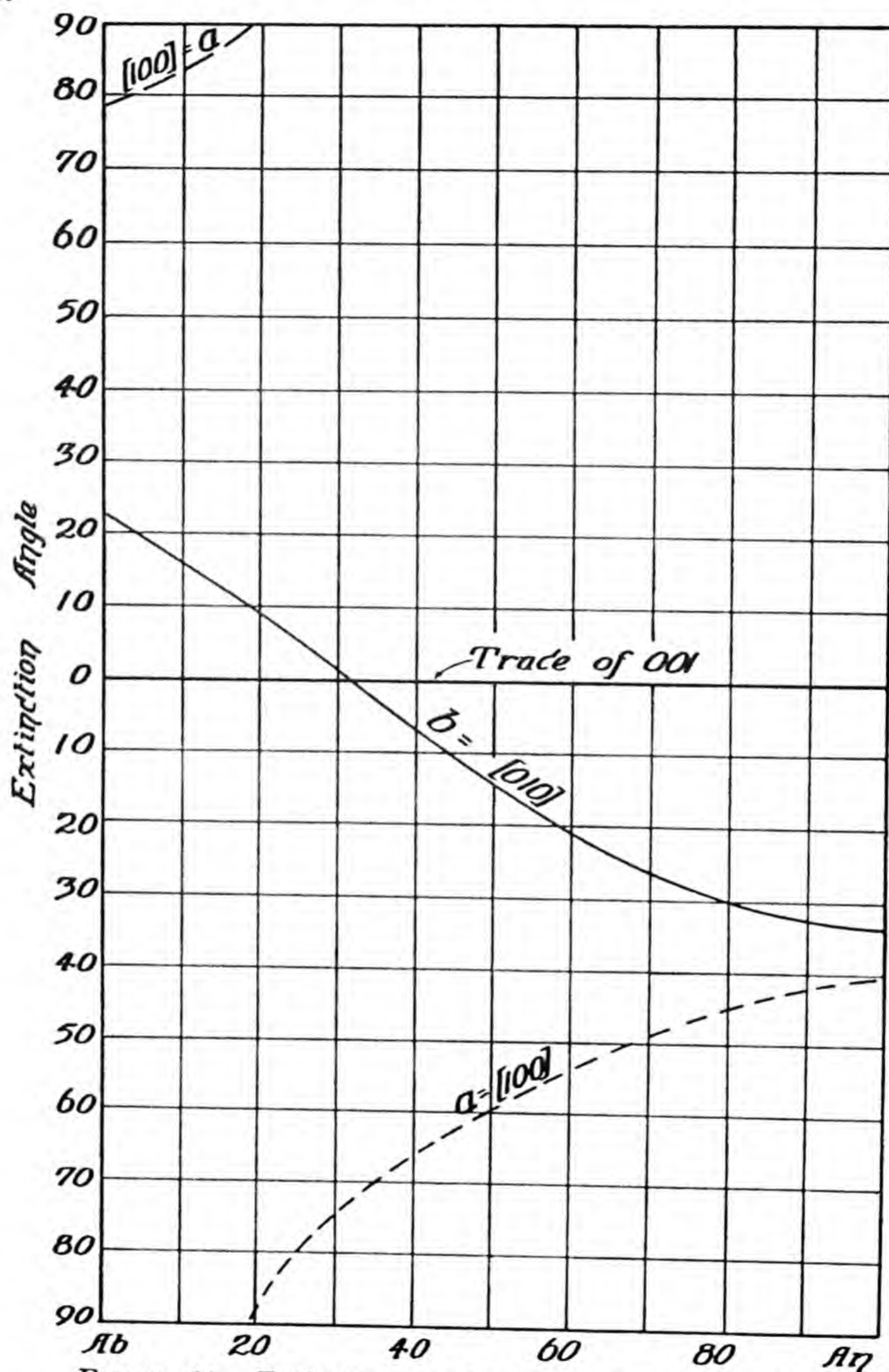
FIGURE 64.—*Extinction angle curves for plagioclase*
Similar to those of Figure 58 but representing an orientation in which (001) is vertical.

If neither transverse cleavage nor twin lamellae are found the maximum or minimum extinction angle for this zone may be determined as was done for the zone ⊥ (010). This maximum or mini-

mum extinction angle is then referred to Figure 52 or 65 using the curve for maximum extinction. Failing this, as illustrated above for the composition face (010), a part of the extinction curve may be construed.
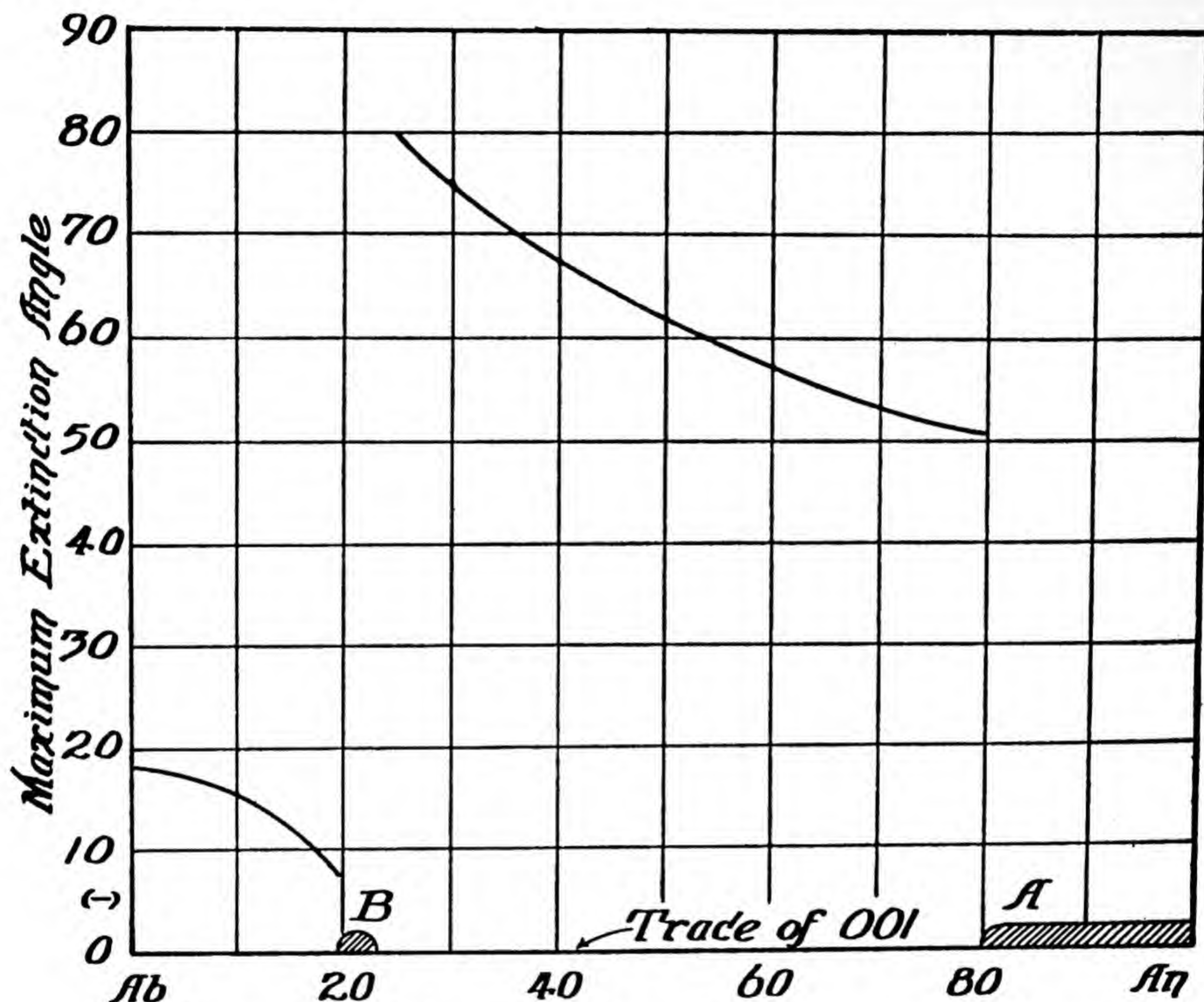
FIGURE 65.—*Maximum extinction angles in the zone* ⊥*(001)*

If the prime purpose is to determine the composition of a plagioclase and if both possible composition faces (001) and (010) are represented by twin lamellae, when the optical character of the zone axis indicates that the chosen composition face is (001) or the rhombic section, a rotation of about 90° may be made on the inner vertical axis thereby choosing the (010) composition face.

Some examples follow:

1. Figure 5 of Plate 7 illustrates a crystal studied above as an example of (010) orientation. The intersecting lamellae may now be studied. They are made vertical by setting the north-south axis at 87°E with an appropriate adjustment of the inner vertical axis. The gypsum plate shows the zone axis to be variable indicating the plane to be (001) or the rhombic section. The cleavage appears parallel to the composition face, eliminating the rhombic section. The intersecting cleavage is

made vertical by a setting on the outer east-west axis at 83°N. The extinction angle of this unit to α' is 54° which gives An_{61} (Fig. 64) compared to An_{59} determined on the (010) composition face.

2. Let us arbitrarily choose the crystal shown in Figure 4 of Plate 7 and studied earlier. The composition face between units one and three was made vertical by setting the north-south axis at 17°E. The zone axis is variable indicating the composition face to be (001). The intersecting composition face is made vertical at 2°N on the outer east-west axis. The extinction angle in this unit in which the intersecting composition face was made vertical is 52°. This indicates An_{65} (Fig. 64).

Two very simple and rapid additional observations reveal the identity of the twin laws. The first leads to a recognition of the twinned relationship of two individuals as (a) normal and (b) parallel or complex. With the composition face vertical and north-south and the microscope stage at its zero position, rotate on the outer east-west axis. Observe carefully the relative intensity of the birefringence colors of the two lamellae of interest. If the two lamellae remain equally bright on this rotation the twin is after a normal law. If the relative brightness of the lamellae varies on the rotation the twin is after a parallel or complex law. (In oligoclase it was pointed out that the optic plane is nearly parallel to (001), and another optic symmetry plane is nearly parallel to (010). Therefore the crystals of this composition are too near extinction for the test to work well.)

The second observation consists merely in measuring the extinction angle of the second twin lamella whose twinned relationship to the first is of interest. If the extinction angle of unit 1, measured to α', is designated E_1 and the extinction angle of unit 2, also meas-

TABLE 11.—*Extinction relations for the zone method*

A. The composition face is (010) oriented to a
   a. A normal twin law.
      1. $E_1 = -E_2$ indicates the *albite law.*
   b. A parallel or complex twin law.
      1. $E_1 > -E_2$ indicates the *Carlsbad law.*
      2. $E_1 > E_2$ "   " *albite-Carlsbad complex law.*
      3. $E_1 = E_2$ "   " *Ala B law.*
      4. $E_1 = -E_2$ "   " *albite-Ala B complex law.*

B. The composition face is (001) oriented to a
   a. A normal twin law.
      1. $E_1 = -E_2$ indicates the *Manebach law.*
   b. A parallel or complex twin law.
      1. $E_1 \lessgtr -E_2$ indicates the *acline law.*
      2. $E_1 \lessgtr E_2$ "   " *Ala A law.*

ured to α', is designated E_2, the relationship between these units is expressed in the relative size and sign of these angles. E_1 is the extinction angle which we have been measuring to determine composition. If the extinction position of unit 2 is on the opposite side of the composition face from that of unit 1, E_2 is regarded as negative, and if it is on the same side as unit 1 it is regarded as positive. E_1 was measured when unit one was oriented to a critical position usually **a**, and E_2 must be measured when unit one is in this same orientation **a**.

The method of interpretation is given in Table 11 for both brevity and clarity.

For still further brevity it is not always necessary to measure the extinction angle of unit 2 for some of the most common twins. When determining whether the twin law is (a) normal or (b) parallel or complex note the nature of the lamellae. There are four cases: (1) Polysynthetic lamellae according to a normal law, with (010) for composition face, indicates the *albite law*. (2) Polysynthetic lamellae according to a parallel or complex law, with (001) for composition face, indicates either the *pericline or acline law*. (3) Two broad lamellae according to a normal law, with (001) for composition face, indicates the *Manebach law*. (4) Two broad lamellae according to a parallel or complex law, with (010) for composition face, indicates the *Carlsbad law*.

When determining the optical character of the zone axis to learn whether (010) or (001) is the composition face, these four cases may be used either as a substitute or for confirmation.

The birefringence of the crystal also confirms the determination of the composition face as (010) or (001). Since the optic plane in the sodic plagioclases is crudely parallel to (001) and since feldspar birefringence reaches a maximum of about .009 and $2V$ ranges around $90°$, rotations on a zone axis which is $\perp$ (001) will yield apparent birefringence of .000-.005, and rotations on a zone axis which is $\perp$ (010) will yield apparent birefringence of .004-.009.

If a given twin is normal the twinning axis is known since it is perpendicular to the composition face. If, however, the twin is parallel or complex the position of the twinning axis may be learned with little effort. With the composition face vertical and either parallel to a nicol or $45°$ to it, rotate on the outer east-west axis to find a position in which the lamellae being studied are equally bright. In this position the twinning axis is either vertical or horizontal. If it is vertical $E_1 = E_2$, if horizontal $E_1 = -E_2$.

It was stated earlier in this chapter that in determining the composition of a plagioclase by means of the extinction angle the direction of the twinning axis can be used in a parallel or complex twin instead of a transverse cleavage intersection or a transverse twin
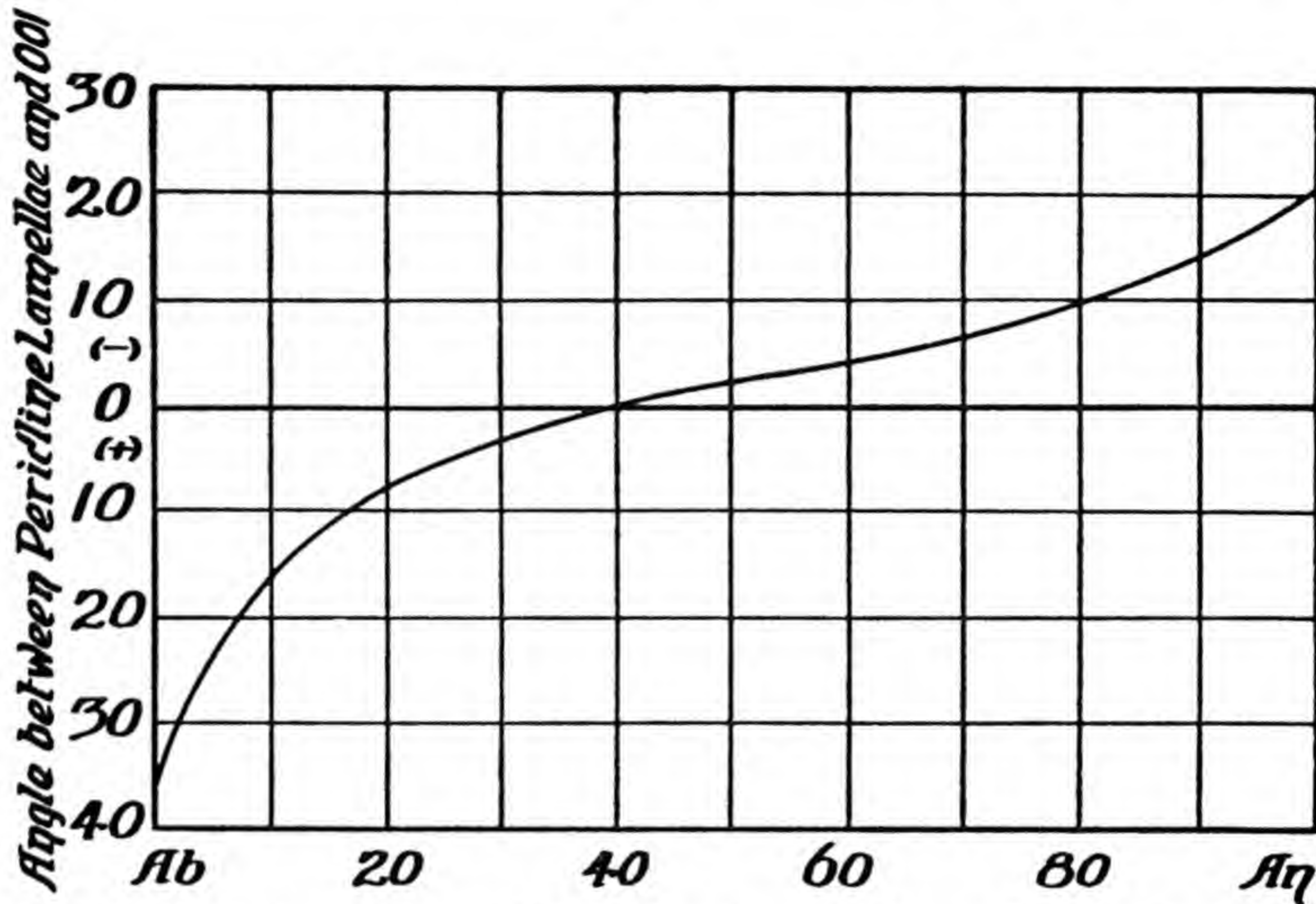
FIGURE 66.—*Curve for angle made by rhombic section with basal cleavage (001) for plagioclase*

lamella intersection with a composition face. After having oriented the first chosen composition face vertically and north-south find the twinning axis. Measure the extinction angle to α' and use the values on Figure 58 or 64 according to the identity of the composition face. Better results may be obtained from the position $\perp$ c than from c.

The angle between (001), usually identified by the cleavage, and the rhombic section can be used to confirm the composition of plagioclase, but care must be taken to measure this angle correctly. It is best done when both (001) and the rhombic section are vertical, in which case the angle is approximately at its apparent maximum as viewed in the microscope. Since the angle can be either positive or negative and ordinarily in rock section it is not possible to know which, it is first necessary to learn whether the plagioclase is more or less calcic than andesine. Hence the use of this must be restricted to confirmatory needs. The angles are given in Figures 66 and 47.

Some examples of the study of twinning by the zone method follow.

1. Figure 1 of Plate 5 shows a crystal twinned according to the pericline law. This crystal is also used later to illustrate the five-axis method which alone is adequate to study it, but it is used here to illustrate one of the points discussed above, namely, by making both the rhombic section (as revealed by the pericline composition face) and (001) (as revealed by the cleavage) vertical, the angle made
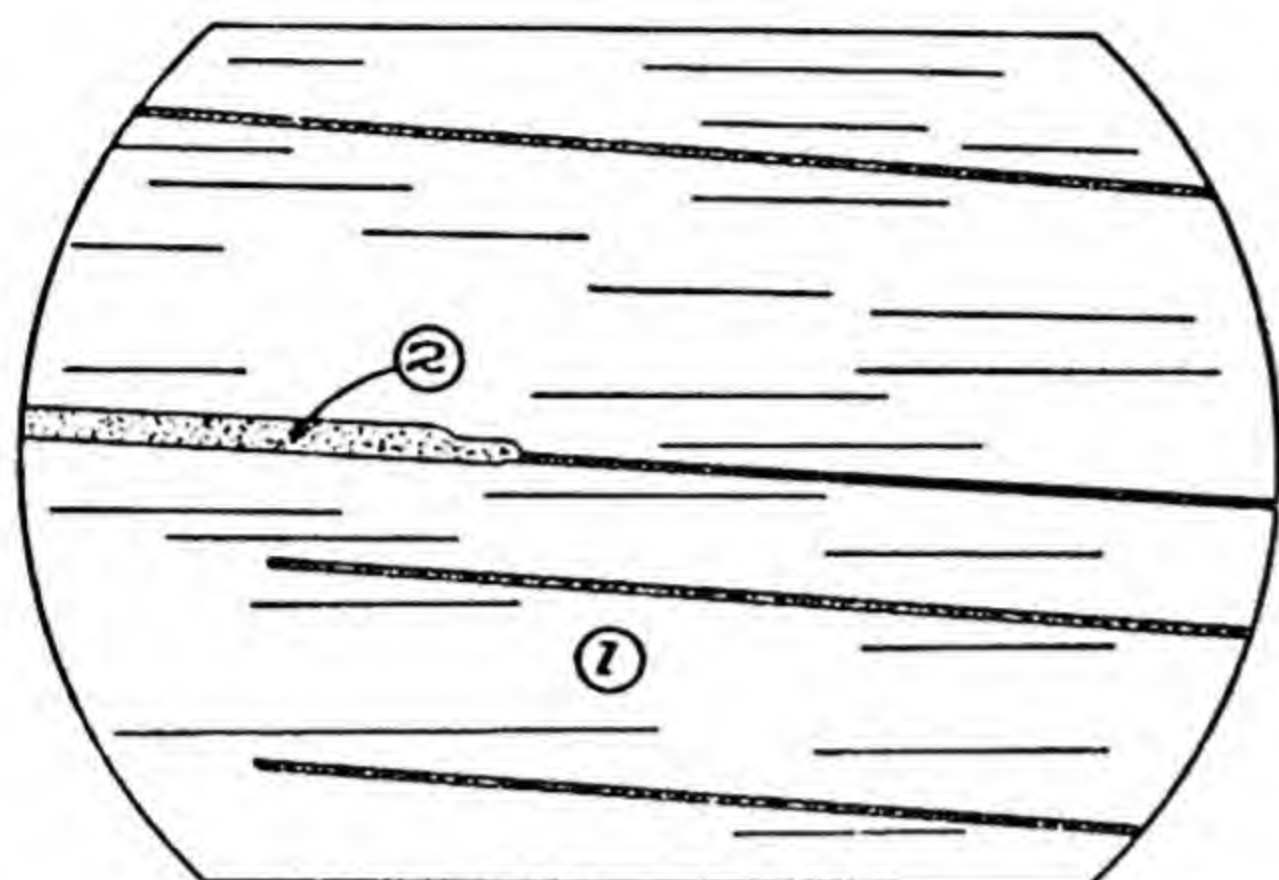
FIGURE 67.—*Key to Figure 1 of Plate 5*
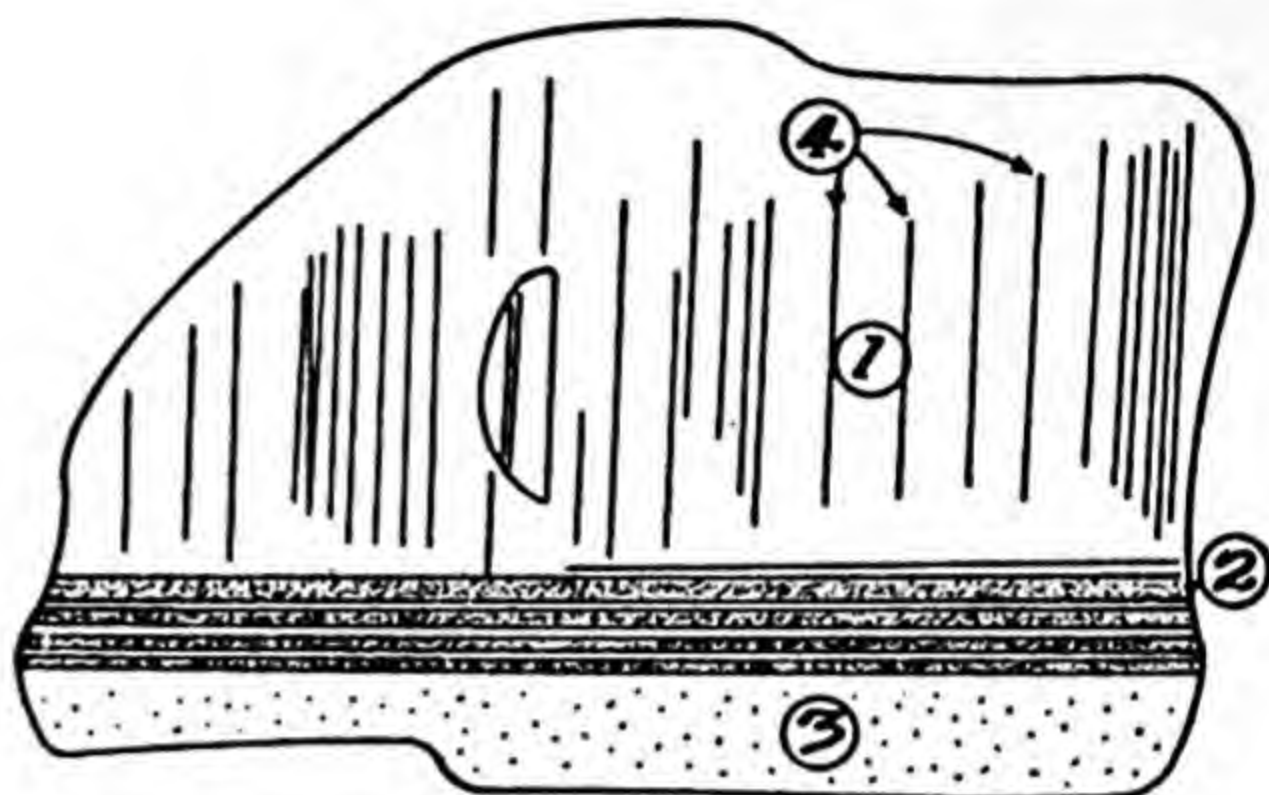
FIGURE 68.—*Key to Figure 2 of Plate 5*

by these two planes, in this case 9-10°, both reveals the twin law as pericline and indicates the composition to be either An_{17} or An_{80} (Fig. 66). It can be seen easily in the photomicrograph that the twin lamellae and the cleavage are not parallel: in fact the angle may be measured in the photo. (*See also* Figure 67.)

2. Let us now complete the study of the crystal shown in Figure 5 of Plate 7. The complete data are as follows:

Comp. face	N-S	O. E-W.	Zone	Class	E_1	E_2	%An	Twin Law.
1-2	28°W	40°N	010	Normal	31°	–31°	59	Albite
1-3	87°E	88°N	001	//	54°	–59°	61	Acline

The determination of the composition was explained earlier. The extinction angles of contiguous units were determined in the orientations in which the composition was determined. From Table 11 we note that for the composition face 1-2, $E_1 = -E_2$, indicating the albite law for a normal twin, and for the composition face 1-3 which was found to be parallel or complex the values are $E_1 < -E_2$, indicating the acline law.

3. For this crystal, shown in Figure 68 and Figure 2 of Plate 5, the data are as follows:

Comp. face	N-S	O. E-W.	Zone	Class	E_1	E_2	%An	Twin Law.
1-2	0.5°E	1°S	010	//	15°	6°	32	Albite-Carlsbad Complex
1-3	"	"	"	//	15°	–7°	32	Carlsbad
2-3	"	"	"	Normal	6°	–7°	33*	Albite
1-4	2°E	2°S	001	//	76°	–86°	29	Acline

* Determined from Rittmann's conjugate curves which are omitted in Figure 58 for simplicity. These conjugate curves are rarely necessary and in practice would not be used here.

This crystal illustrates the best points of the Rittmann method. The acline lamellae are extremely narrow, and even though they are on edge it is difficult to determine their exact extinction position. The conjugate acline extinction angle is several degrees in error, but the error does not lie in the method. The other lamellae give results of a quality that is to be expected—*i. e.*, ±8% An. The table is self evident, and the details are similar to those of the other examples.

The twin laws, unless rare, may be learned readily by this method as the examples show.

Chapter 8
Five Axis Method of Feldspar Study[6]

THIS method was originally devised to study the narrow twin lamellae of the Duluth gabbro—lamellae which are too narrow to be studied by the Fedorow method, since they cannot be oriented optically, and too calcic for study by the Rittmann zone method. This new method was found to be so direct and so generally satisfactory that it has been used in the writer's laboratory to the complete exclusion of the Fedorow method and it has largely supplanted the Rittmann method (Emmons and Gates, 1939).

Whereas the Fedorow method involves the orientation of related twin lamellae, this method requires the orientation of only one. The Fedorow method involves the graphing of each lamella, its rotation, and graphical compilation. From this compilation the twinning axis is deduced. The five-axis method leads directly from the orientation of one lamella to the instrumental location of the twinning axis. In actual practice the five-axis method is not only much faster and less tedious but avoids the inevitable errors in lengthy graphical construction. In general, we have found results from this technique to be much more consistent.

The five-axis method is less rapid than the Rittmann method on very simple twins. In studying complex twins it is as rapid and in very complex crystals it is more rapid. Since most crystals studied are relatively simple, the Rittmann method is more rapid in general. The five-axis method is equally effective on calcic and sodic crystals. It will reveal immediately a rare or new twin law or any other irregularity, as does the Fedorow method, and it is direct. The Rittmann method lacks these advantages.

The five-axis method is based on the following facts:

1. Twinning axes either lie in the composition face or are normal to it, leading to the classification parallel, complex, and normal.

2. In a parallel or complex twin the relative birefringence colors of adjacent lamellae change under the following condition of rotation —the composition face made vertical and parallel to a nicol and rotated on a horizontal axis normal to it. Under the same conditions birefringence colors of the adjacent lamellae of a normal twin also change, but they rise and fall together. This information

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[6] Several details with which the experienced operator is already familiar are omitted here to be covered in Chapter 9.

reveals the exact position of a normal twinning axis and limits the parallel or complex twinning axis to one plane.

3. In parallel or complex twins the change in interference colors of adjacent lamellae may be used to locate the twinning axis. When
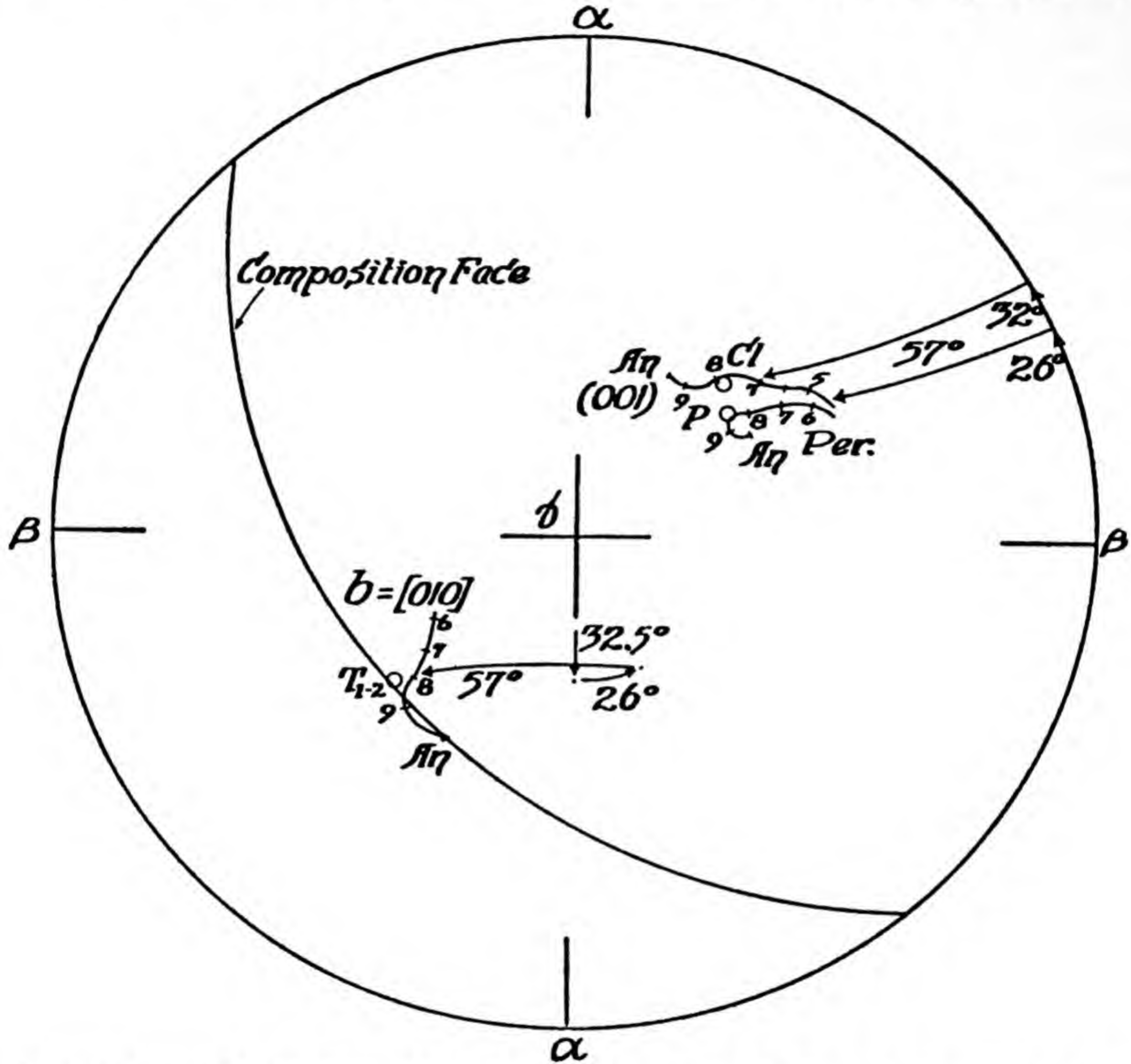
FIGURE 69.—*Stereogram of crystal in Figure 1 of Plate 5 (Recorded in Table 12)*

Only the poles and axes are plotted in routine work, and none of the plot lines shown here. Cl-cleavage, P-pole of a plane, T-twin axis. (In this and in several succeeding examples the hemispheres are 1.559. Corrections are therefore negligible and are omitted to avoid detracting from the main thought. They would ordinarily be neglected in practice also.)

the interference colors of the adjacent lamellae are identical the twinning axis is either horizontal or vertical—assuming, as in 2 above, that the composition face is rotated in a vertical position on a horizontal axis which is perpendicular to a nicol. The same is true if the composition face is 45° to a nicol.

4. If a parallel or complex twinning axis is vertical, both lamellae extinguish together; if horizontal, the extinction angles are equal and opposite, on rotation of the microscope stage.

TABLE 12.—*Twin determination—Five axis method*

(Figs. 67 and 69)

Reference Data: 38 −6B   Split Rock Point, Minn.

Hemispheres: 1.559   Zero Values: Mic. 0°   O. V. 90°

Unit 1:

I. E–W	15° S
N–S	39° W
O. A. 1	43° N
2	
	2V: —
O. V	(
O. E–W	
M	(

I. V.	12°
α	N
β	E
γ	⊥
Bx$_a$	
Sign	
β	
2V	

Comp. Face 1.	O. V.	26° (	
	N–S	(18°+39°=)57° E	
	I. E–W	— —	
Twin Axes (O. E–W)	1–2	32.5° N	V
Cleav =		32° (, 57° E	

See Figure 67
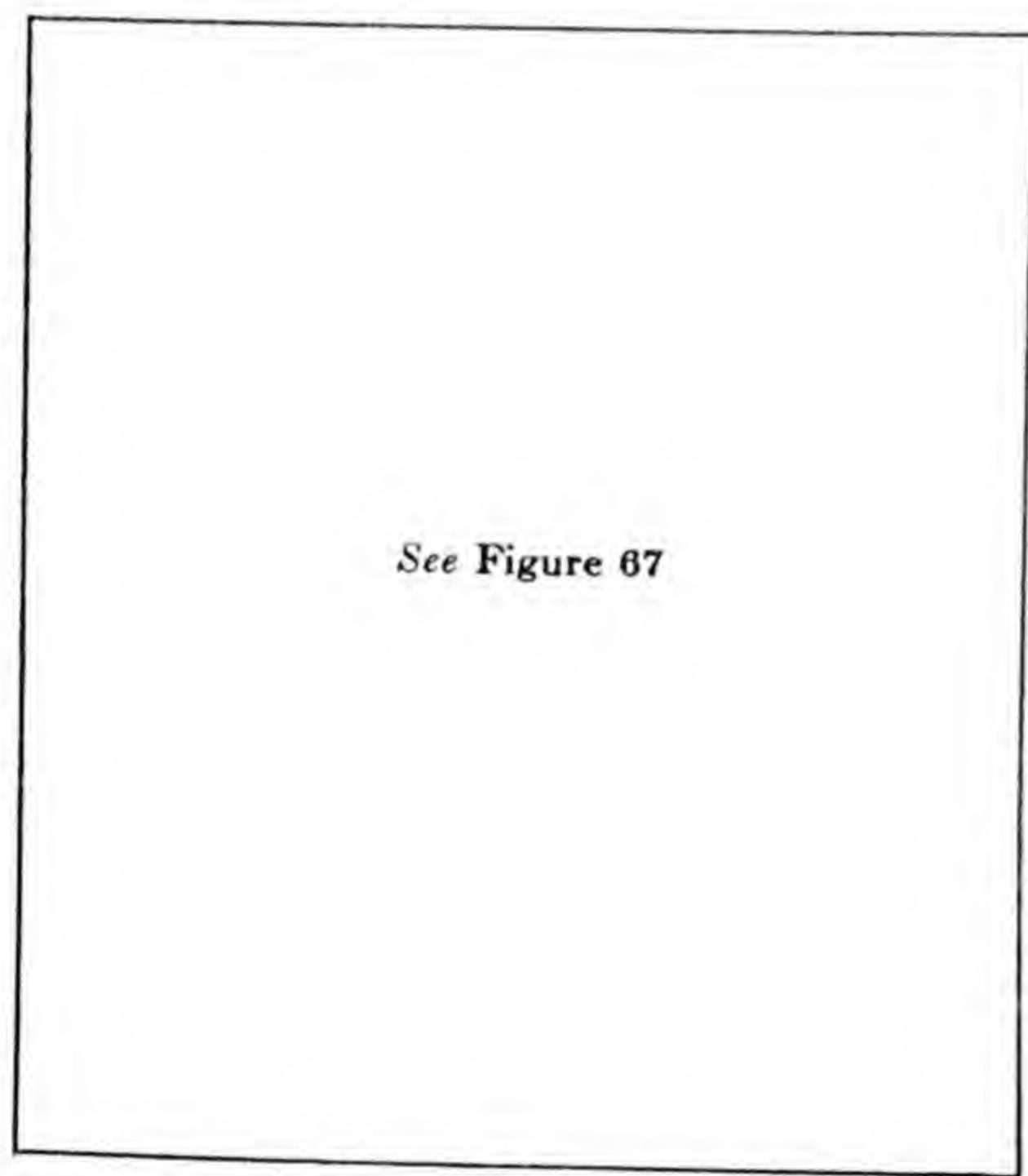
Comp. Face 2.	O. V.	
	N–S	
	I. E–W	
Twin Axes (O. E–W)		

Remarks:

The instrumental procedure is as follows: Choose one unit of the crystal for orientation on the basis of good optical qualities, such as freedom from strain, freedom from inclusions, breadth of one or more lamellae adequate for wide rotations without interference, and
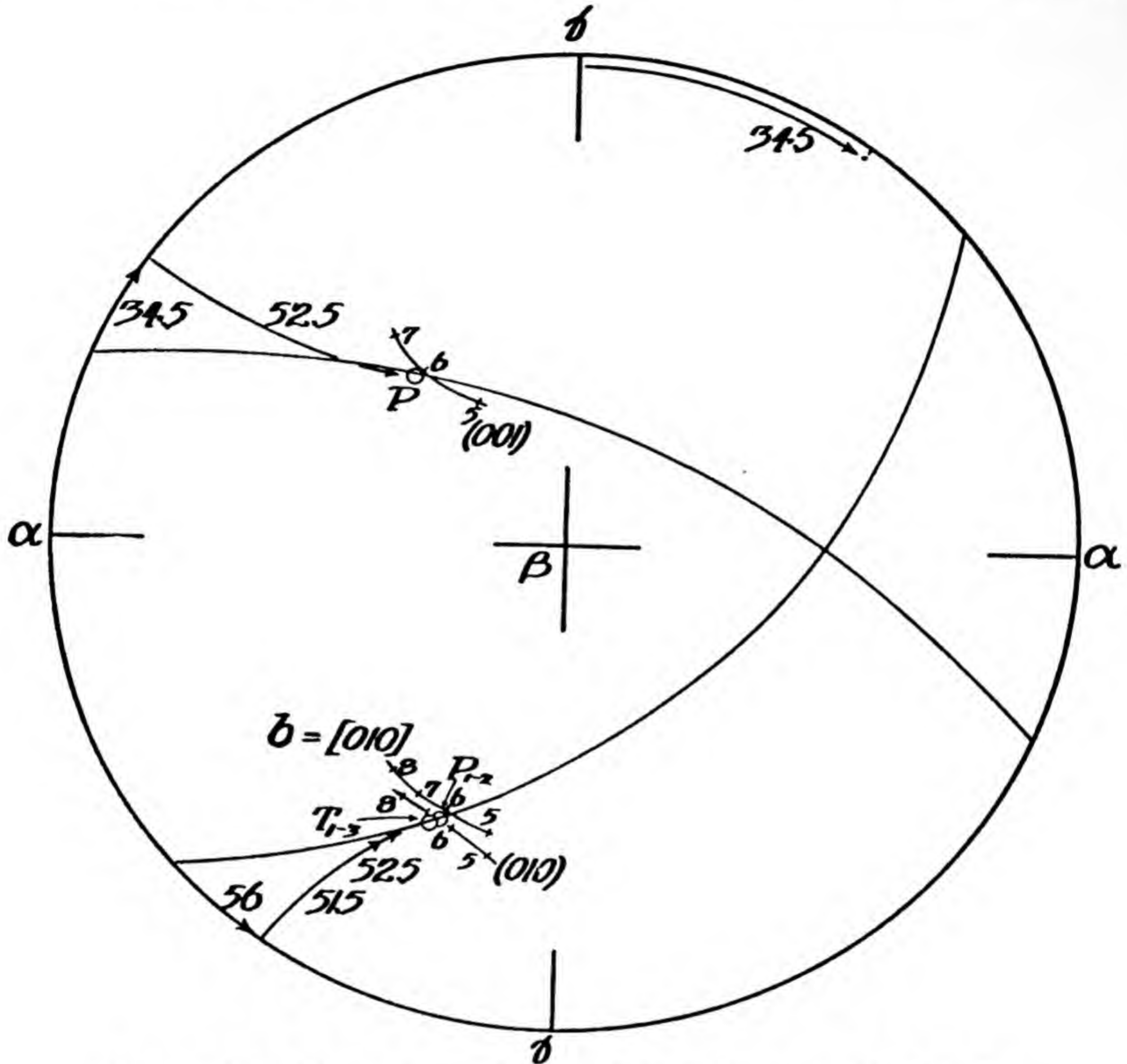
FIGURE 70.—*Stereogram of crystal in Figure 4 of Plate 7*
This typical example emphasizes the direct simplicity of the method. The data are given in Table 18.

especially for its contacts with other units of the twinned crystal. Although any unit of a twinned crystal bears a twinned relationship to all other units, nevertheless it is better to limit the statement of relationships to those units which are in actual contact at a composition face. The selected unit, which may be numbered "one" for reference, may be oriented well and quickly if chosen wisely. All succeeding results depend on this one orientation. If a record is to be kept a sketch may be made on the data sheet, and the units numbered.

Orient unit one and record the data on the data sheet (Form 4).

TABLE 13.—*Twin determination—Five axis method*

(Figs. 59 and 70)

Reference Data: Duluth Gabbro, Birch Lake, Superior National Forest
Hemispheres: 1.559   Zero Values: Mic. 0°   O. V. 90°

Unit 1:

I. E–W	11° N
N–S	42.5° E
O. A. 1	
2	
	2V: —
O. V	⊂ 45°
O. E–W	54.7°S
M	⊂ 43°

I. V.	356°
α	E
β	⊥
γ	N
Bxₐ	N
Sign	(+)
β	
2V	84°

Comp. Face 1.	O. V.	34.5° ⊂	
	N–S	10° W+42.5°	
	I. E–W	— —	
Twin Axes (O. E–W)	1–3	1° N	H

See Figure 59
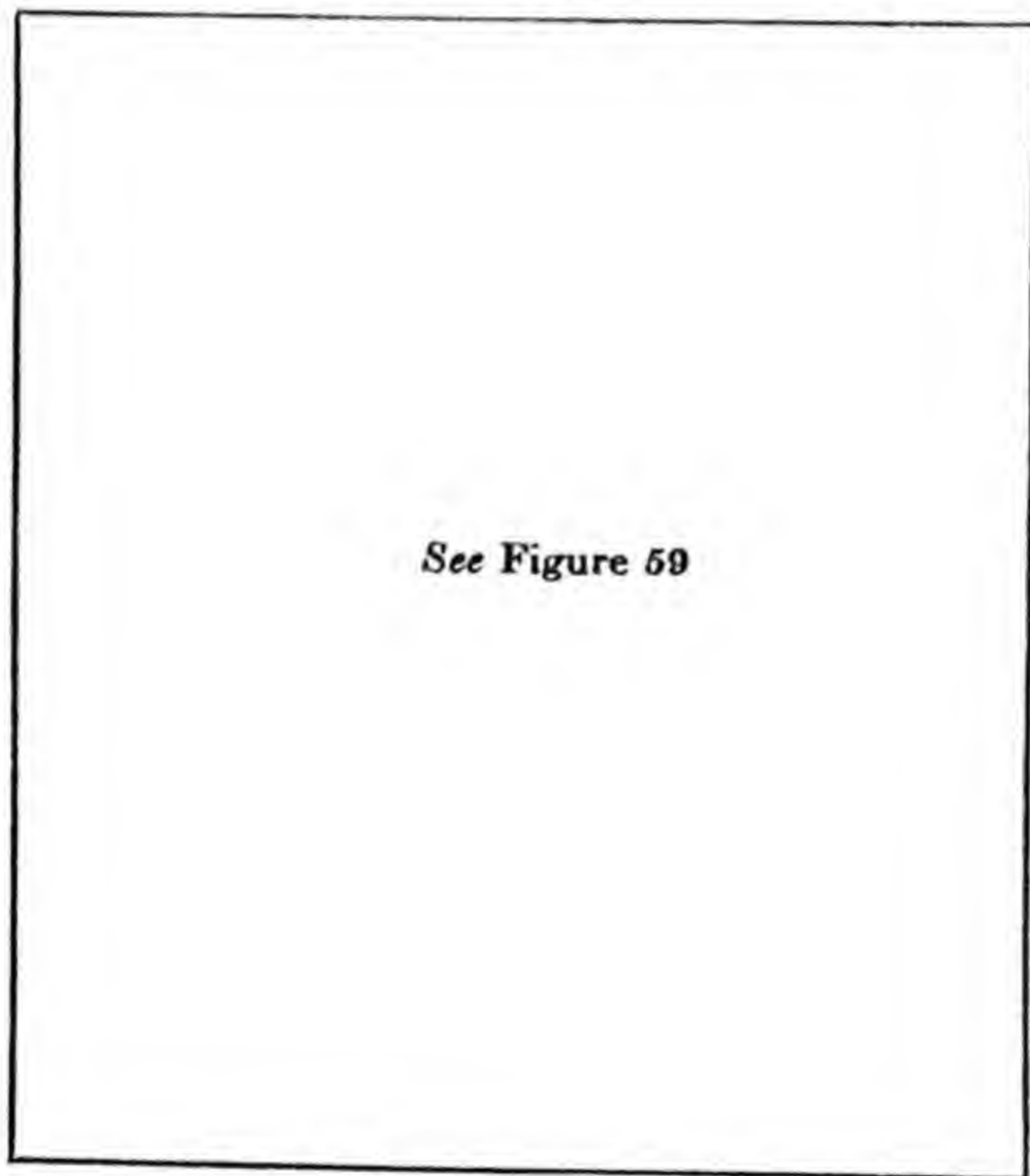
Comp. Face 2.	O. V.	56° ⊃	
	N–S	9° W+42.5°	
	I. E–W		
Twin Axes (O. E–W)	1–2	Normal	

Remarks:

Determine α, β, and γ by any suitable method—the Berek or Dodge procedure and the gypsum plate are as rapid as any. Then orient the first composition face, making it vertical and north-south, using the north-south and outer vertical axes. Record the data.
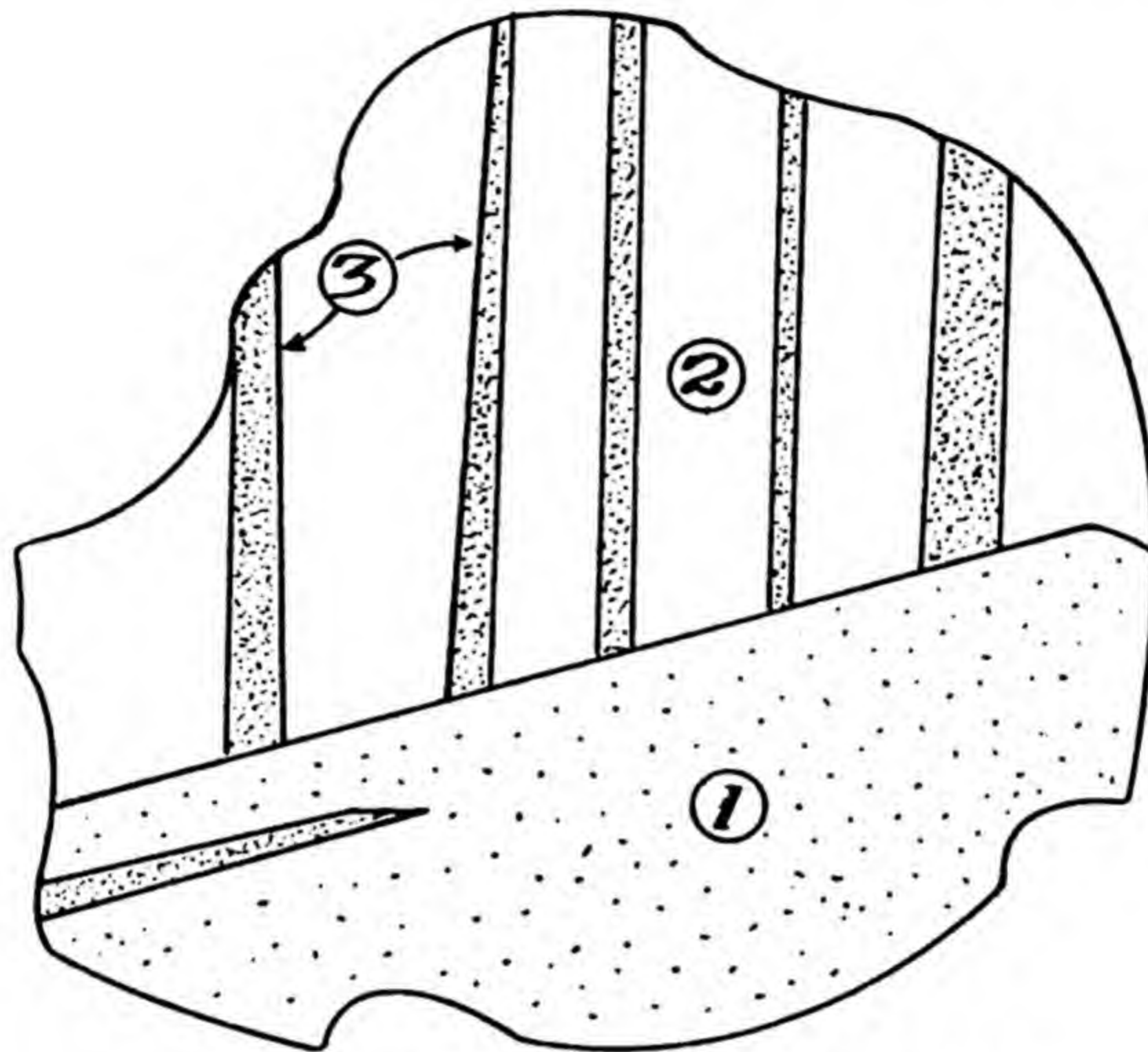
FIGURE 71.—*Key to Figure 2 of Plate 7*

Rotate on the outer east-west axis and observe the interference colors of the two units being studied. If they rise and fall together indicating a normal twin, then enter the word "normal" in the appropriate column. If, on the other hand, the interference colors change relatively as the rotation on the outer east-west axis is made, the twin law is parallel or complex, and a position on this rotation is sought where the two lamellae being studied agree in interference color. This value is inserted on the data sheet. The twinning axis is now vertical or horizontal. Lastly, the extinction angles of the two lamellae are determined. If the values are equal and opposite the twinning axis is recorded as horizontal. If the values are equal and of the same sign the twinning axis is vertical.

The same observations are made for each composition face and for each pair of lamellae to be studied.

Sometimes in attempting to make a composition face vertical the two suggested axes (outer vertical and north-south) do not give adequate rotation. In that case set the north-south axis at zero and use the outer vertical and inner east-west axis. This change in the procedure is especially desirable when the strike of the com-

position face is east-west. It is to be avoided when possible because it adds one more step to the graphical record which follows.

During the procedure an alternate step may be recorded. When finding the twinning axis by making the rotation on the outer east-west axis to observe the relative interference colors of the two lamellae being studied, the observation is sometimes better made when the composition face is at 45° to the nicols instead of parallel to one. If the parallel position does not yield a satisfactory identity of interference colors try the 45-degree position, but the 45-degree position must be measured and not estimated.

There remains only to represent the recorded data on a stereogram and apply the stereogram, as is done in the Fedorow procedure, to a compilation of migration curves. The construction of the stereogram is as follows:

The laboratory may be supplied with stereographic blanks (Form 3), stereographic nets (Pl. 9), and stereograms of migration curves (Pl. 12). In the writer's laboratory a complete set of migration curve stereograms and two sets of nets are permanently mounted on light tables, covered with cellophane to prevent soiling and wear. The blanks are to be superposed on the nets on the light tables. Rotations may be measured without the confusion of the net lines being added to the blanks since the blanks consist of a circle, identical in radius to that of the net, with the cardinal points and the center indicated.

On the blank are noted α, β, and γ, as on the compilation sheet in the Fedorow procedure. The face poles and the twinning axes are to be located to complete the drawing. The necessary data are on the data sheet. There are three ordinary cases: (1) to plot the face pole and the twinning axis of a normal twin, (2) to plot the twinning axis of a parallel or complex twin when the data indicate it to be vertical, (3) to plot the twinning axis of a parallel or complex twin when the data indicate it to be horizontal. If the instrumental procedure required the use of the inner east-west axis this constitutes a second group: (4)-(6) to plot poles and axes when the north-south axis is set at zero.

The beginner may find the order of the graphical rotations confusing, and an error here leads, of course, to complete failure. Since the Fedorow stereographic net provides for graphical rotations on only three mutually perpendicular axes (north-south, east-west, and vertical), each graphical rotation is possible only if the axis involved is graphically in one of these three cardinal positions. If in doubt set the instrument, or a model, according to the data of a given

case. Make first a rotation on the innermost axis which is in a cardinal orientation. If a rotation is to be made on the inner east-west axis and the data indicate that the north-south, outer vertical, and outer east-west axes are inclined, then since the inner east-

FIGURE 72.—*Stereogram of crystal in Figure 2 of Plate 7 (Table 14)*

west axis is dependent on (supported by) each of these, each of them must be reduced to its zero position before the inner east-west rotation may be made. Otherwise the inner east-west axis is inclined, and the Fedorow net is not adapted. Furthermore, in bringing these supporting axes to zero, the same rules of order must be applied. To any who have used the stereographic projection successfully in an elementary course in mineralogy, there are no difficulties.

Let us consider the cases listed above:

(1) To plot a face pole or a normal twinning axis. The purpose in all cases is to locate the desired pole in the position which it occupied when the crystal was optically oriented. Since its posi-

TABLE 14.—*Twin determination—Five axis method*

(Figs. 71 and 72)

Reference Data: 38 — 52

Hemispheres: 1.559   Zero Values: Mic. 0°   O. V. 90°

Unit 1:

I. E–W	39° S
N–S	20° W
O. A. 1	38° N
2	
	2V: —
O. V	(
O. E–W	
M	(

I. V.	330°
α	N
β	E
γ	⊥
Bx$_a$	
Sign	
β	
2V	

Comp. Face 1.	O. V.	7.5° (	
	N–S	19.5°E (20–0.5°)	
	I. E–W	— —	
Twin Axes (O. E–W)	1–2	4° N	V

See Figure 71
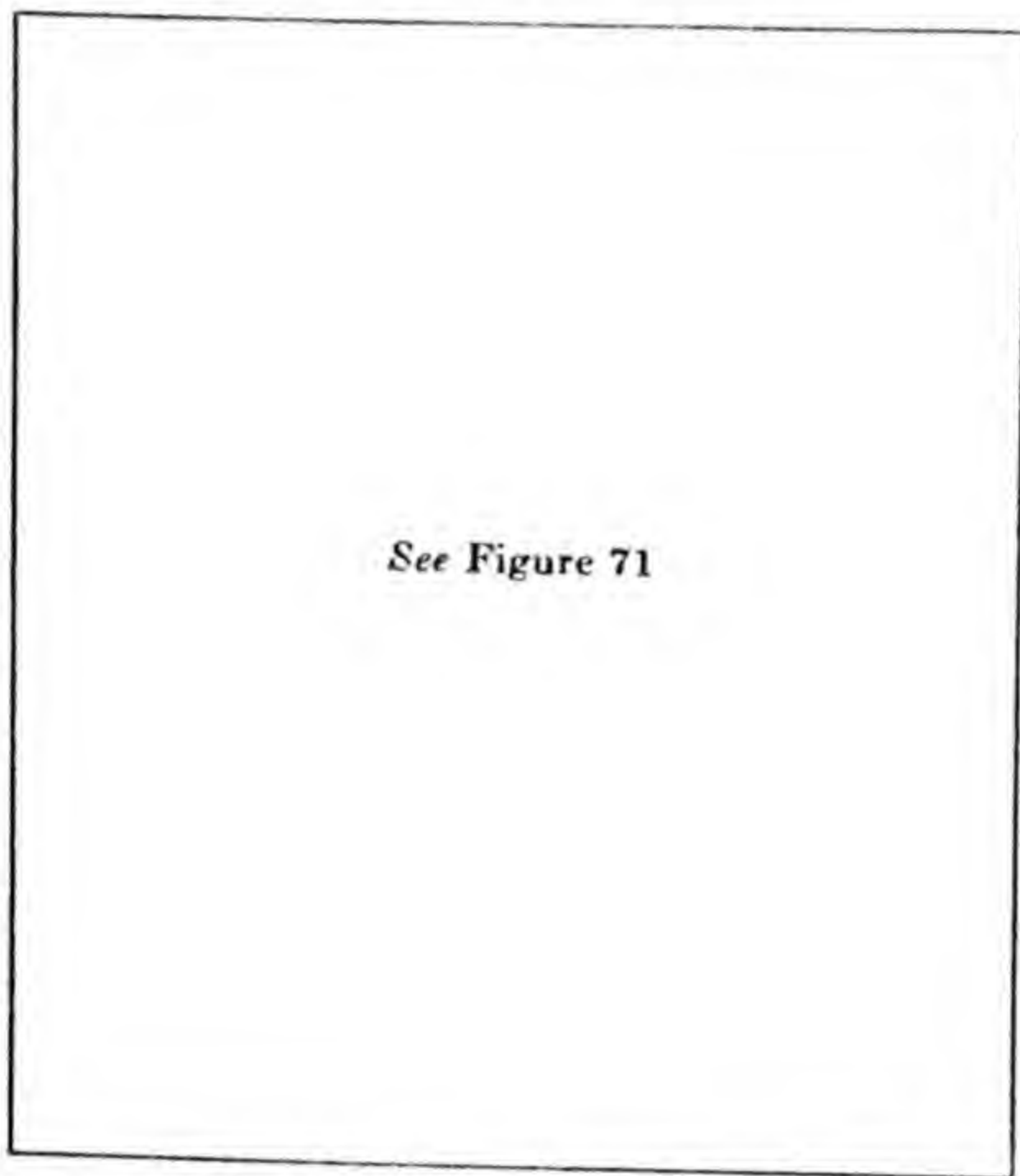
Comp. Face 2.	O. V.	83° (	
	N–S	(20°E)	
	I. E–W	(52°+39°) = 91°N	
Twin Axes (O. E–W)	2–3	Normal	

Remarks:

tion at the end of the procedure is known, it is necessary to reverse the readings as recorded in the last column of the data sheet. The pole is east-west when the composition face is vertical and north-south. Starting at one of these points (east or west), reverse the reading on the outer vertical axis following the outermost circle
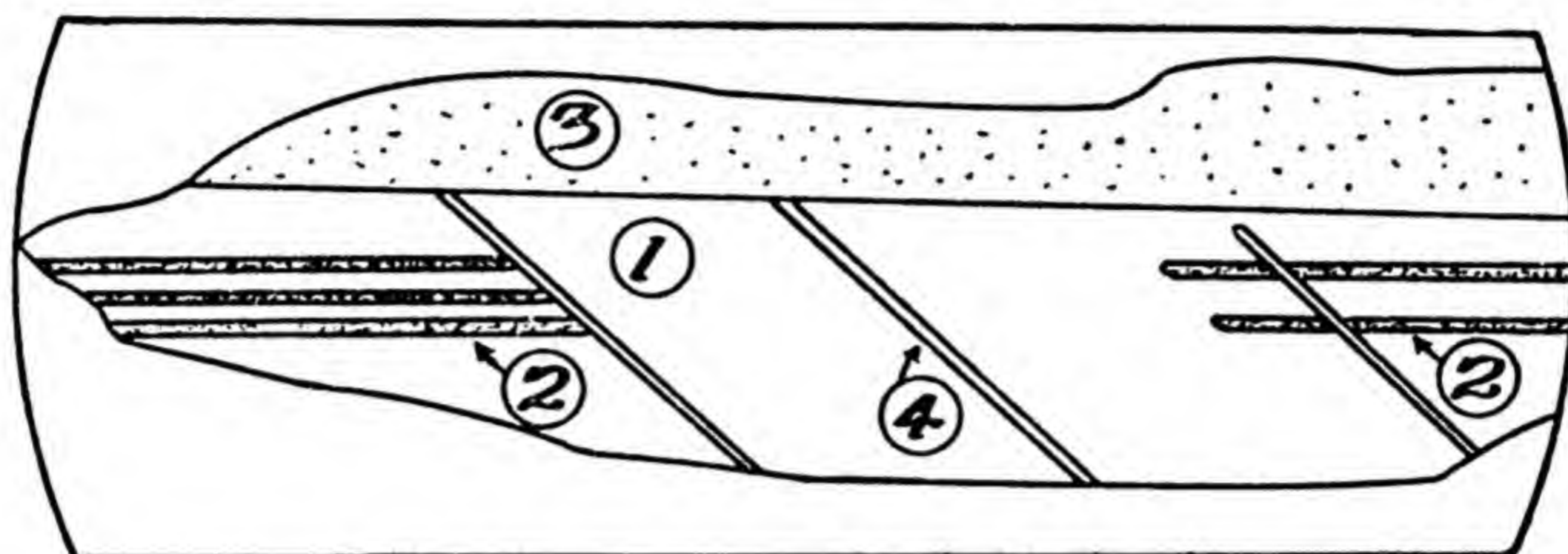
FIGURE 73.—*Key to Figure 3 of Plate 7*

and measuring on the radials. This returns the outer vertical axis to its zero position. Next reverse the reading on the north-south axis following one of the east-west small circles and reading on the north-south great circles. The originally chosen point was the east or west pole according to the north-south reading. If the north-south axis reading is x°E, start at the east pole, satisfy the outer vertical reading, and reverse the north-south reading which then carries the point to the west. These two rotations locate the pole of the face and the normal twinning axis.

The blank may then be superimposed on the proper stereogram of the migration curves as for the Fedorow procedure. Here lies the great advantage of the Fedorow procedure—that the actual face pole and twinning axis is related directly to the other crystallographic elements. The full value of this part of the Fedorow procedure is preserved in this five-axis method, but a short cut is provided around the lengthy details.

In superposing the blank on the migration-curve stereograms the proper stereogram must of course be selected, and one of four positions of superposition must be selected. This is discussed in Chapter 9 and will not be repeated here.

(2) To plot the twinning axis of a parallel or complex twin when the data indicate it to be vertical. Since the twinning axis is vertical start with a point at the center of the net. Reverse the outer east-west axis reading which carries the point north or south on the net. This brings the outer east-west axis to its zero position and makes the outer vertical axis vertical. Next therefore reverse the outer vertical axis reading, following a concentric circle and measuring on

the radials. This brings the outer vertical axis to its zero position and makes the north-south axis north-south. Lastly, reverse the north-south axis reading as given in the last column, following as always an east-west small circle and measuring on the great circles. The blank is now ready to be superposed on a migration curve stereogram.

(3) To plot the twinning axis of a parallel or complex twin when the data indicate it to be horizontal. This case differs little from the last. Instead of starting at the center of the net we start at the north or south pole—the north pole if the recorded reading on the outer east-west axis was to the north, and the south pole if the recorded reading on the outer east-west axis was to the south. When the reading is reversed the point is carried toward the center of the net. Fundamentally both are of course the same. The remainder of the plotting is the same as in the last case, the outer vertical reading being satisfied next, and lastly the north-south axis reading.

(4) To plot the pole of a normal twin when the north-south axis is set at zero and the inner east-west axis is employed. Again as in case (1) the composition face is made north-south and vertical, and its pole is therefore east and west. Starting at one of these points as before we satisfy the reading on the outer vertical axis as was done in case (1). This brings the outer vertical axis to its zero position and makes the north-south axis north-south. Since, however, the north-south axis was set at its zero position the inner east-west axis is horizontal and east-west. Next, therefore, the reading on the inner east-west axis is satisfied. This reading of course includes the original setting, either by addition or subtraction. To accomplish this on the net recommended here and provided in Plate 9 the blank must be rotated 90° since only one set of small circles is provided. Follow the appropriate small circle and measure on the great circles, turning the blank back for the next step. This rotation on the inner east-west axis brings that axis back to its proper reading when the crystal was oriented. Now satisfy the north-south axis reading— this when reversed becomes the same as the original north-south axis reading in the left-hand column—the original setting for unit one. This is done as before on small circles and measured on great circles.

(5) To plot the twinning axis of a parallel or complex twin when the data indicate it to be vertical and the inner east-west axis is employed. As in case (2) we start at the center. First satisfy the reading on the outer east-west axis, then the reading on the outer vertical axis as in case (2). Next, however, as in case (4), the reading

on the inner east-west axis is satisfied, and lastly, the north-south axis reading as given in the left-hand column.

(6) To plot the twinning axis of a parallel or complex twin when the data indicate it to be horizontal and the inner east-west axis is
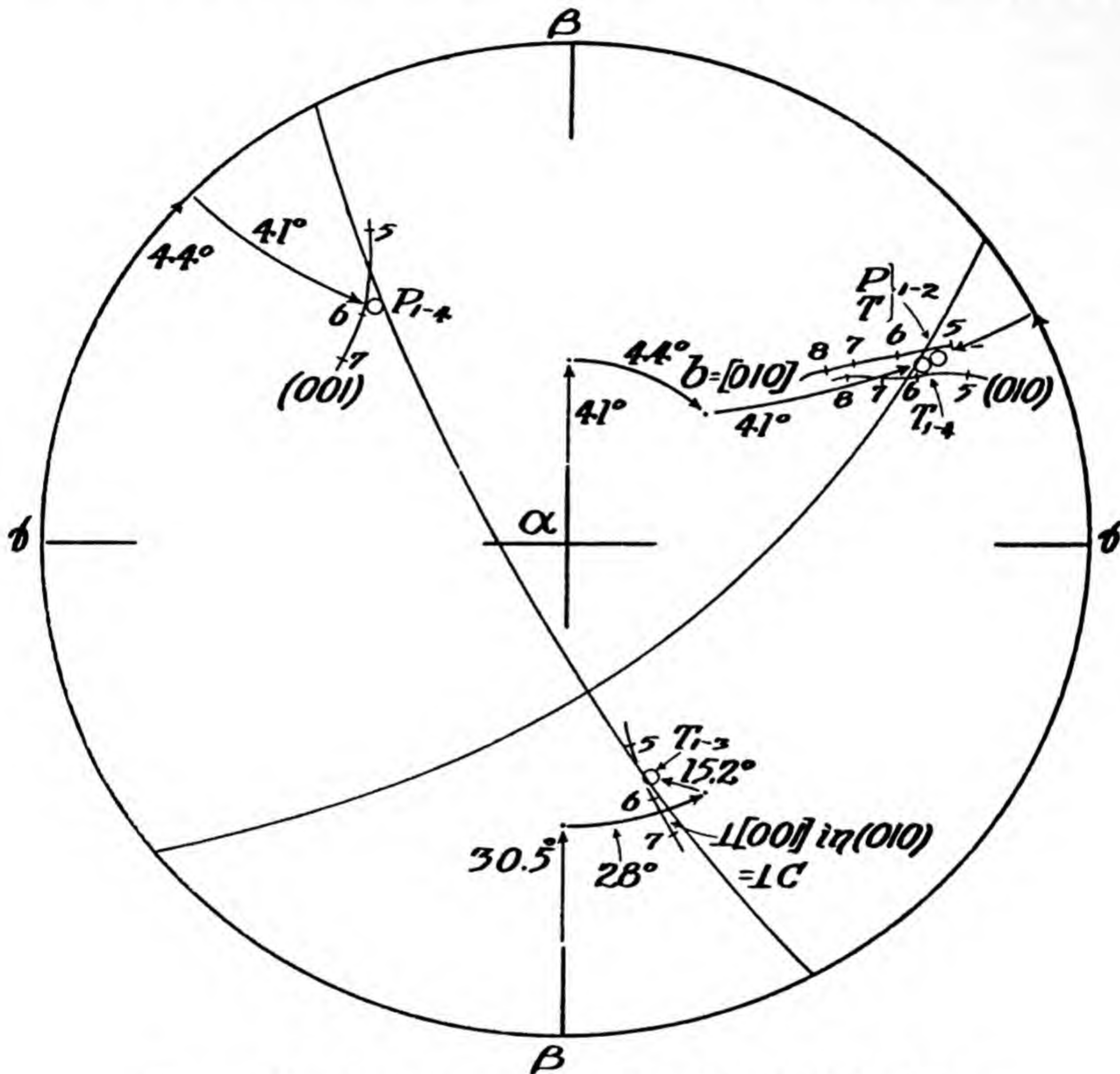
FIGURE 74.—*Stereogram of crystal in Figure 3 of Plate 7*
From data of Table 15. Preferred method of orientation.

employed. This case differs from case (5) precisely as case (3) differs from case (2). It is, therefore, self-evident.

These procedures will be further explained in the following examples.

1. This crystal was employed earlier to illustrate the use of the angle made by the basal cleavage and the rhombic section as represented by pericline twin lamellae. It is illustrated in Figure 67 and in Figure 1 of Plate 5. The lamellae are too narrow to be studied by the Fedorow method. The Rittmann method was tried with the following results: There is no available intersecting cleavage or twin lamellae, the maximum extinction angle is indefinite because of broad regions of extinction, but b is available, though by the Rittmann method this will not reveal the twin law. Only the composition of this crystal may be learned by the extinction angle or the intersection of the cleavage and rhombic section. But if

TABLE 15.—*Twin determination—Five axis method*

(Figs. 73 and 74)

Reference Data: 37 −29
Hemispheres: 1.559   Zero Values: Mic. 0°   O. V. 90°

Unit 1:

I. E–W	36° N
N–S	12.8° E
O. A. 1	53° W
2	
2V: —	
O. V	(
O. E–W	
M	(

I. V.	352°
α	⊥
β	N
γ	E
Bxₐ	
Sign	(+)
Nn	
2V	

Comp. Face 1.	O. V.	28° (
	N–S	(28° − 12.8° =)15.2°E
	I. E–W	— —
Twin Axes (O. E–W)	1–2	Normal	
	1–3	30.5° S	H

See Figure 73
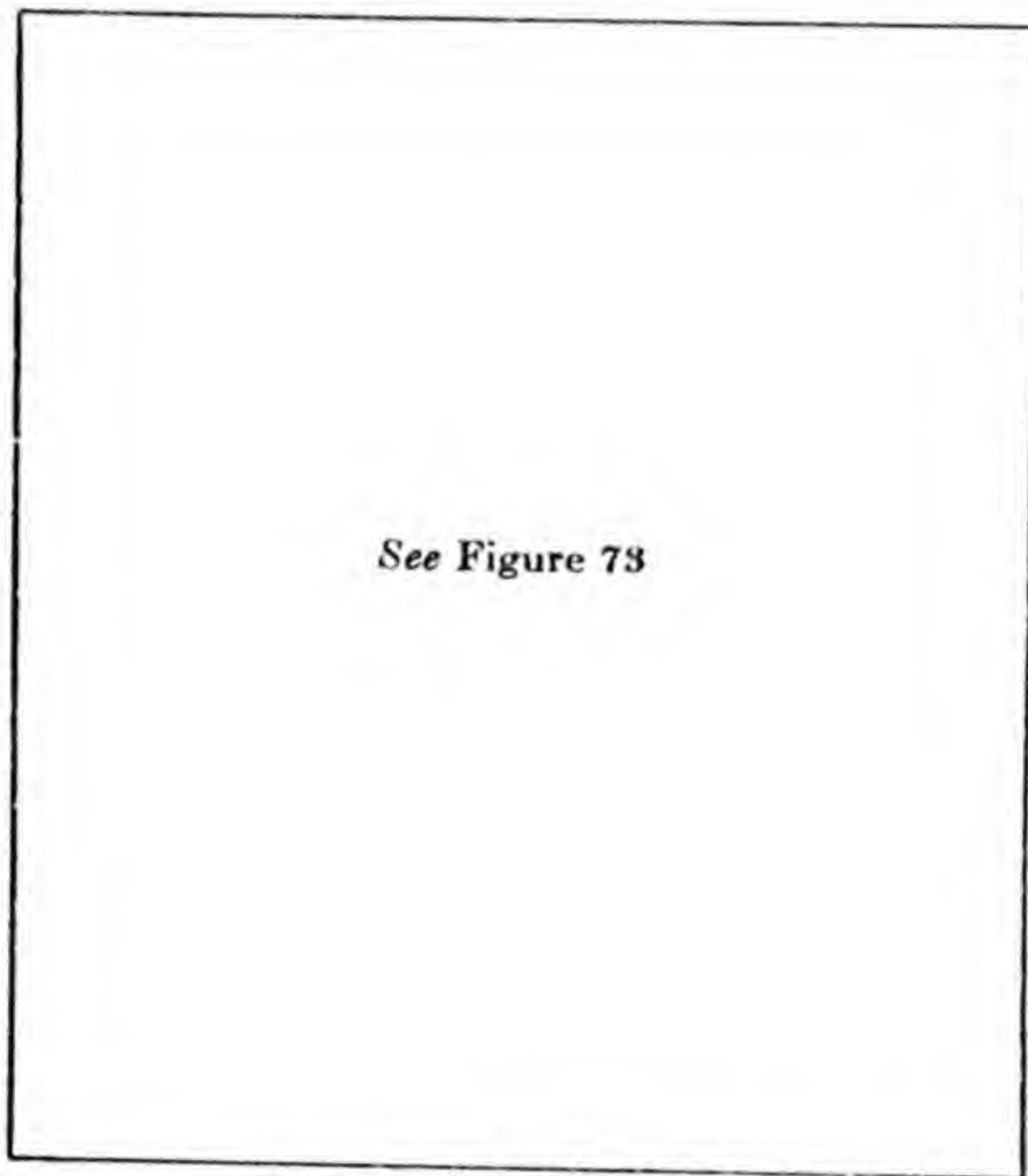
Comp. Face 2.	O. V.	44° (
	N–S	41° W (28+12.8°)
	I. E–W	— —
Twin Axes (O. E–W)	1–4	41° S	V

Remarks:

the twin lamellae are broad enough for microscopic visibility the law may be learned by the five-axis method.

In Figure 69 a stereographic blank expresses the data of Table 12. The course of the plotted points is also indicated, though ordinarily only the final position is noted. This drawing, together with the discussion of plotting given above (Cases
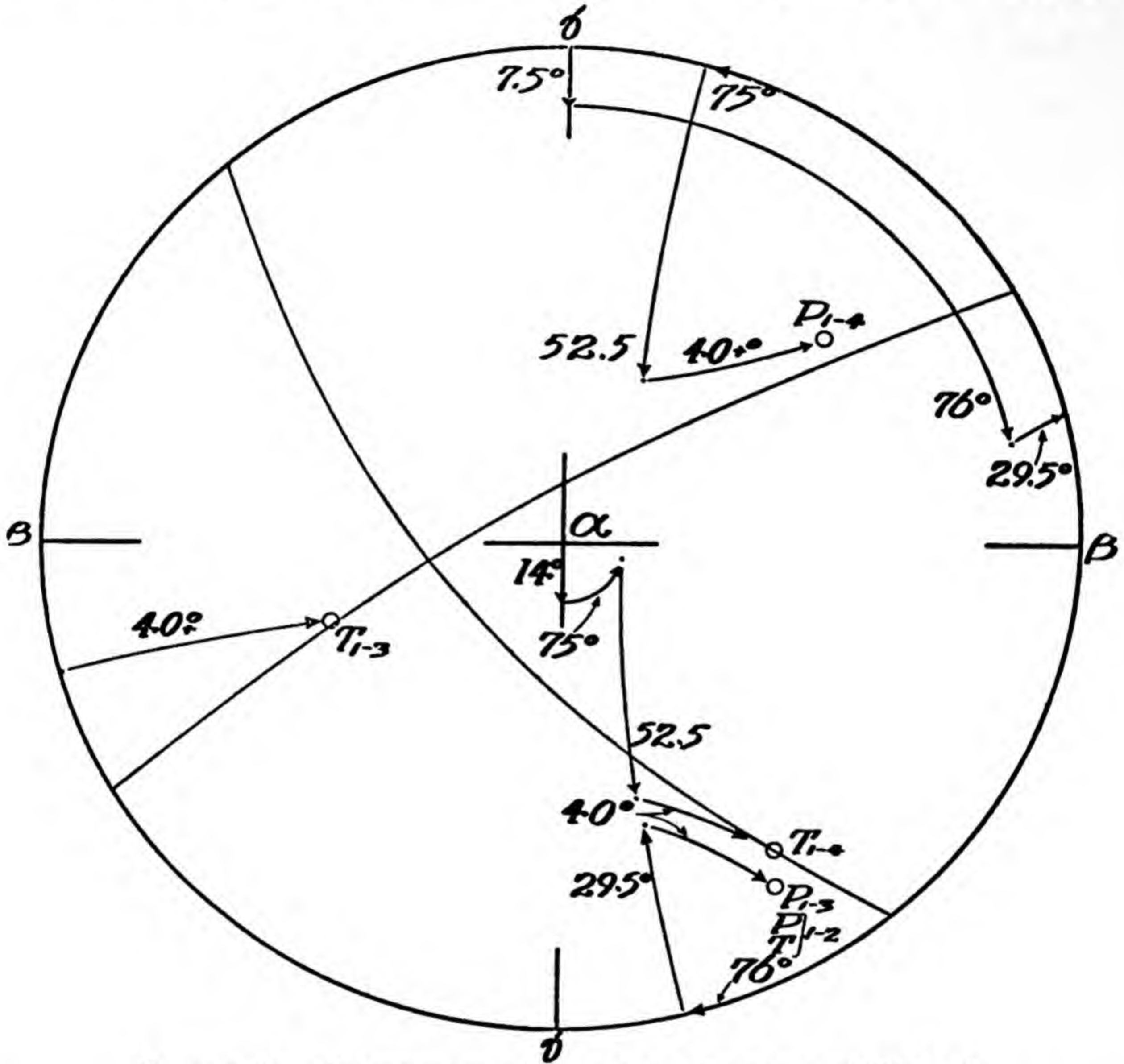
FIGURE 75.—*Stereogram of crystal in Figure 3 of Plate 7*
From data of Table 16. Procedure employs the inner east-west axis. Not the preferred method of orientation.

1 and 2), is adequate explanation. The appropriate migration curves are also added to show the degree of agreement that may be expected.

2. The crystal shown in Figure 59 and Figure 4 of Plate 7 has been studied by the Rittmann method. The data given in Table 13 are plotted with the courses of the plotted points in Figure 70. They are cases (1) and (3). The order for the plotted points to find the twinning axis 1-3 is as follows: 1°S, 84.5° clockwise, and 52.5°E, which carries the point to the opposite side of the projection.

3. This is illustrated in Figure 71 and Figure 2 of Plate 7. The data given in Table 14 are plotted in Figure 72. Cases (2) and (4) are represented. In Figure 72 the pole of the composition face 1-2 falls so close to both the rhombic section and the face (001) for this composition that it is impossible to tell whether the twin law is acline or pericline. So far as we know *now* it is relatively unimportant which law is represented, especially for compositions near andesine.

TABLE 16.—*Twin determination—Five axis method*

(Figs. 73 and 75)

Reference Data: 37 −29
Hemispheres: 1.559   Zero Values: Mic. 0°   O. V. 90°

Unit 1:

I. E-W	10.5° S
N-S	40+° E
O. A. 1	52° N
2	
2V: —	
O. V	(
O. E-W	
M	(

I. V.	75°
α	⊥
β	E
γ	N
Bxa	
Sign	
β	
2V	

Comp. Face 1.	O. V.	76° (	
	N-S	(40+° W)	
	I. E-W	(40° − 10.5°) = 29.5°S	
Twin Axes (O. E-W)	1-2	Normal	
	1-3	7.5° N	H

See Figure 73
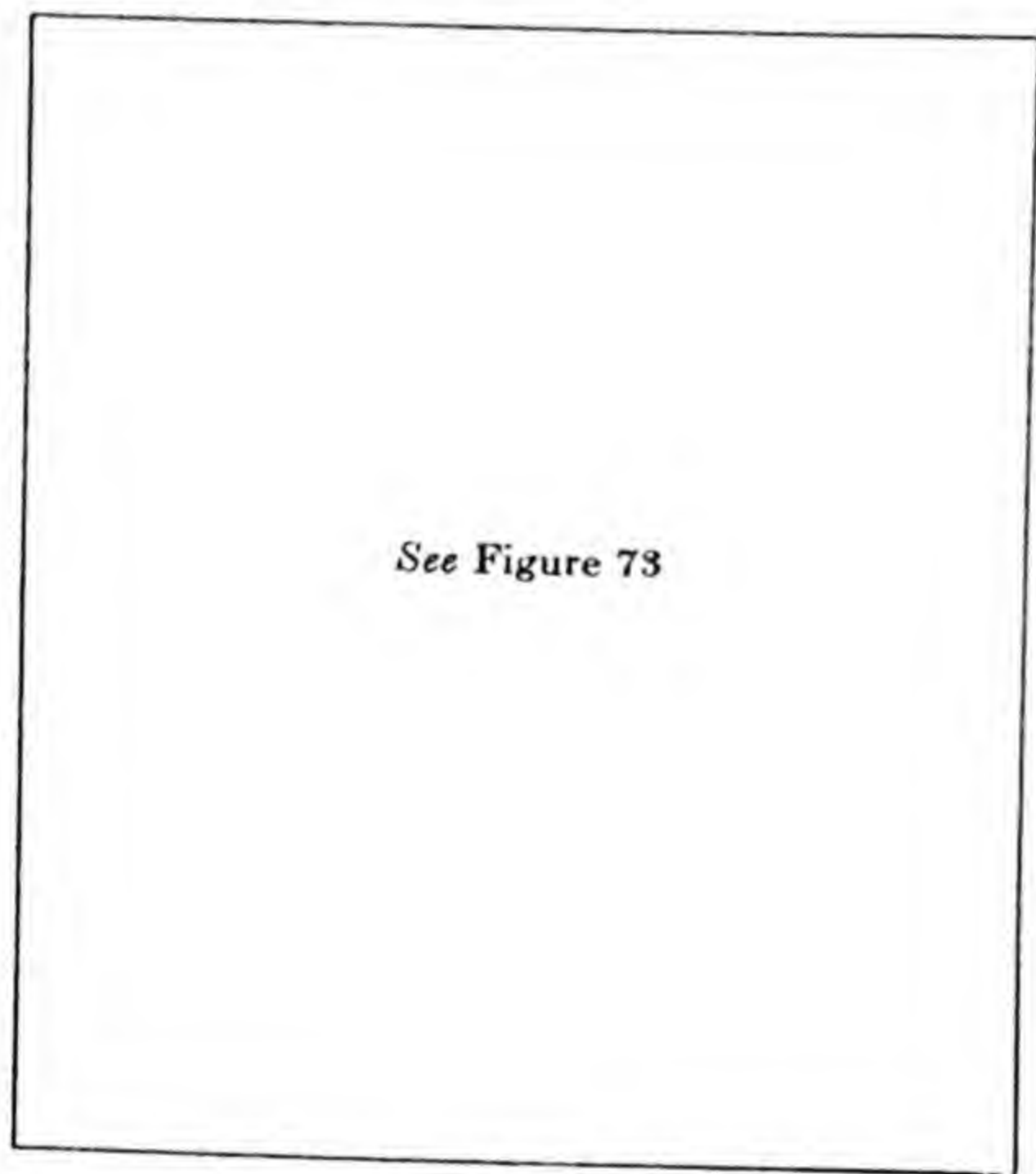
Comp. Face 2.	O. V.	75° (	
	N-S	(40+° W)	
	I. E-W	(42° + 10.5°N) = 52.5°N	
Twin Axes (O. E-W)	1-4	14° ±N	V

Remarks:

More data are of course plotted in Figure 72 than are plotted in routine work.

4. This crystal (Fig. 73; Pl. 7, fig. 8) illustrates both available extinction positions for orientation and further details of the procedure. In Table 15 are given the data for the preferred method of orientation—that which does not require the use of the inner east-west axis for determination of the twinning axes. These data plotted in Figure 74 are cases 1, 2, and 3 and are easily understood.

In Table 16 are the data for the other orientation, which leads to a condition in which the composition face (010) trends east-west. Therefore a rotation on the north-south axis is very ineffective in making this plane vertical, and the inner east-west axis must be used. The east-west direction is first made north-south by a rotation of 75° on the outer vertical axis. Since this axis carries the north-south and inner east-west axes, they become reversed in position, and a rotation on the inner east-west axis effectively modifies the attitude of (010). The north-south axis is preferably, but not necessarily, first set at 0°. The data plotted in Figure 75 are cases 4, 5, and 6.

After the (010) composition face of example 4 is made vertical, as in the other examples the crystal is rotated on the outer east-west axis to locate the twinning axes. Two settings on this axis are illustrated: In Figure 1 of Plate 6 the two parts of the Carlsbad twin are in contrasting illumination. In Figure 2 of Plate 6 the same two parts are in equal illumination. The two settings are only a very few degrees apart. After obtaining the position of equal illumination there remains only to measure the extinction angles of the two parts; as indicated on the data sheet by the entry "H" the angles are equal and opposite. It should be observed too that the unit 4 lamellae are extremely fine as can be seen from the photomicrographs.

Lastly, this crystal is used to illustrate the technique for making a composition face vertical. This is, as has been stated, difficult, but accuracy is necessary. The most commonly employed criterion is the sharpness of the composition face as the crystal is inclined to make the composition face vertical. Three stages of inclination show how the composition face narrows as it becomes vertical (Pl. 6, figs. 5-7). The composition face is that of the Carlsbad twin. Magnification is 400×. A 20× objective (special in all makes) and at least a 10× ocular give the best results. The average of several readings should be used.

The various possibilities have now been described and illustrated. It is emphasized that this method, since it uses the Fedorow stereograms, embodies all the complete coverage of that method, at the same time increasing the accuracy and greatly speeding the determination by eliminating very many steps. Although ordinarily less rapid than the Rittmann zone method, it does not have the limitations of that method.

Chapter 9
Fedorow Method of Feldspar Study

SINCE feldspars, especially plagioclases, are apt to be tabular parallel to (010), they appear elongate in thin section, the elongation indicating roughly the attitude of the side pinacoid.

Two cleavages are commonly observed in thin-section study of feldspars: parallel to the basal pinacoid (001) and the side pinacoid (010). The cleavage (001) is the more prominent, though both are easily seen when favorably oriented. Cleavage may be invisible when inclined only a few degrees to the axis of the microscope. It is parallel to the axis of the microscope when the lines defining it are sharpest. The determination of parallelism is sometimes sharpened by the appearance of a bright line analogous to the Becke line.

Although plagioclase feldspars are not always twinned, they so commonly are that twinning is used as the readiest criterion for their identity, the most frequent composition faces being (010), (001), and the rhombic section. As brought out by Manolescu (1934), however, high magnification shows that in detail these composition faces are not strictly parallel to the pinacoids but follow vicinal faces somewhat irregularly. This is especially true of composition faces parallel to (010), and it therefore robs them of their value when they are used for the accurate determination of a crystallographic plane. For general determinations, however, they are extremely helpful. Cleavage planes more clearly approximate true crystallographic planes than do composition faces, and of the cleavage planes (001) is preferred. Therefore, when determining the anorthite content of a plagioclase as outlined below, choose first the cleavage (001), then cleavage (010), then twinning axes, and last the composition faces.

Possibly the most popular method of feldspar determination is that of immersing a cleavage fragment in an oil of suitable refractive index and thereby determining the indices of the crystal on the cleavage. The curves provided by Tsuboi or similar curves are then used to interpret the results. However, it is commonly required to learn the identity of a given feldspar, especially a plagioclase, in thin sections where the procedure is not quite so simple. Extinction angles are then used on oriented sections, but oriented sections are not always easily found since they must be recognized by means of interference figures, by statistical search, or equal extinction

angles. Furthermore, it is commonly desirable to know the composition of a particular feldspar crystal in a thin section, and that crystal may not be suitably oriented. Accordingly we welcome the universal stage method, devised by Fedorow and strengthened by the invaluable contributions of his students, though others have also approved and enhanced the method by applying it to their own problems. Special credit is due Nikitin. The study of feldspar is overwhelmingly the main use that the early workers made of the instrument.

In principle the Fedorow universal stage method of feldspar determination consists in orienting a feldspar crystal optically and relating this orientation to a crystallographic plane or line. For orthoclase, microcline, and their varieties this relationship is relatively fixed; for plagioclase the relationship varies with composition.

The orientation of the optic elements of plagioclase, with respect to the crystallographic elements, depends upon the composition of the crystal. Since the routine procedure requires optical orientation, we may better express this concept as follows: If, on a stereographic projection of a plagioclase crystal in which the optical elements (α, β, and γ) occupy the cardinal positions, we plot the pole of a crystallographic plane, then the position of the pole will depend upon the composition of the plagioclase. Detailed study by earlier workers has led to the development of "migration curves" for these poles. Along these curves the anorthite content of plagioclase is noted (Pl. 12, figs. 1-6). By merely plotting the poles the composition of a plagioclase may be learned in terms of the anorthite content. Greater accuracy is, however, to be hoped for in the future, since quite commonly a plotted pole is noticeably off a migration curve though the optical procedure is quite satisfactory. The explanation is not entirely apparent, but it may be due to the elements of the composition not taken into consideration, such as the potash content, or it may be due to hidden strain in the crystal, or it may be due to some element not yet understood. A combination of these factors with emphasis on the last is probably the real explanation.

In spite of the tremendous amount of work done on feldspars there is yet a great deal of a fundamental sort to be learned about them. We are unable by any optical method yet published to learn reliably the potash content of a plagioclase feldspar or the soda content of an orthoclase. Although the relationship between the optical and crystallographic properties of feldspar is in general well known, there are strong indications of the irregularities mentioned above in determined data. A very disturbing occurrence of such

variations is in adjacent twin lamellae which may differ optically in composition by more than 10 per cent. It is difficult to explore this question chemically because of lack of suitable material. However, despite the most serious limitations we know, the method of Fedorow offers us generally adequate reliability and convenience second only to the immersion method. If a practical use or significance is found for the ubiquitous feldspar twinning, this method of identification will become even more important.

The procedure involves little that has not been discussed in the use of the universal stage, but it does require that the data be plotted on the stereographic projection. For determinative purposes this is all and is as simple as making the corrections discussed in Chapter 4. To determine the twin laws by the Fedorow method, however, the use of the stereographic projection is more involved.

A feldspar crystal which does not show a cleavage plane, a composition face, or a crystal face is not adapted to the technique, but such a crystal is fortunately quite unusual. Orient the crystal and identity α, β, and γ. It is convenient to use the Berek method as an integral part of the technique, but it is also satisfactory to search the two vertical symmetry planes for optic axes through a rotation of 60° from the oriented position. Figure 10 is a modification of Figures 11 and 14 to adapt them to feldspar study more specifically for the use of the Berek method. On a blank with which the laboratory may be supplied, record the data on the orientation (Form 2).

The attention may next be directed to the cleavage and composition face. Sometimes a composition face and frequently a cleavage plane is not evident unless the plane is steeply inclined. It is well therefore to search by wide rotations for such planes if satisfactory ones are not apparent. The purpose in this step is to make such a plane vertical (*i.e.,* parallel to the axis of the microscope) and parallel to a cross hair. When so oriented the pole of the plane is in a cardinal position. Although the trace of one of these planes may be made parallel to a cross hair with suitable ease, it is much more difficult to make the setting parallel to the axis of the microscope in a section of standard thickness. Some prefer to cut sections of special thickness, even as much as .1 mm. thick. Although this is satisfactory for plagioclase of coarse twinning, it is most undesirable for those having fine twin lamellae, since it hampers the orientation procedure. For sections of standard thickness, the following details will usually prove sufficient. Observe carefully the thickness of the trace of the cleavage or other reference plane on rotation on a horizontal axis. When the plane is truly vertical (parallel to the axis of the

microscope) the trace is thinnest and sharpest, assuming indefinite boundaries when inclined either way. Distinct cleavage planes commonly affect the transmission of light in a definite manner when near the vertical position. A white line, similar to the Becke line, either disappears or appears on both sides of the cleavage trace when the plane is vertical. When the plane is inclined the white line appears on one side only. For accuracy the orientation of this visible reference plane should be done with care; it is well to average readings.

Two axes are used to orient the crystallographic reference plane; they are either the outer east-west and the outer vertical axes or the north-south and the outer vertical axes according to which cross hair is used. It is usually preferable to use the cross hair nearer to the trace of the plane. Record the two readings. The outer vertical axis reading will be expressed in degrees clockwise or counter clockwise measured from the position of orientation. The outer east-west axis reading will be expressed in degrees north or south, or if the north-south axis was used it will be expressed in degrees east or west *from the oriented position*. Since the north-south axis is always inclined to start with this reading is the result of an addition or subtraction of the original (orientation) reading and the new reading. These readings indicate that if the orientation of the crystal is affected by these values the crystallographic reference plane is now so oriented that its pole is parallel to one of the cross hairs. Since we want the locus of the pole when the crystal is oriented, these two new readings may then be reversed. On a stereographic net locate the pole—it is one of the cardinal points. Let us consider two cases: (1) Composition face is 23° N., 34° ⟨; (2) Composition face is 23° E., 34° ⟨.

(1) From the north point of the stereographic net read south 23°. From this point read clockwise 34° on one of the concentric circles, measuring on the radials. The point so located indicates the pole of the reference plane *when the crystal was oriented*. Spot this point and mark on the net α, β, and γ, which will of course be at the cardinal points.

(2) From the east point of the stereographic net on the outermost circle read 34° counter clockwise measuring on the radials. Then following the small circles which are concave to the north read 23° westward on the great circles which are concave to the west. The point so located is the locus of the pole of the reference plane when the crystal was oriented. Spot the point on the net and indicate α, β, and γ as before.

Note especially the difference in the procedure in the two cases and that the directions read on the instrument are reversed (Fig. 76). All readings on horizontal axes are of course to be corrected. Information thus far obtained gives α, β, and γ and the attitude
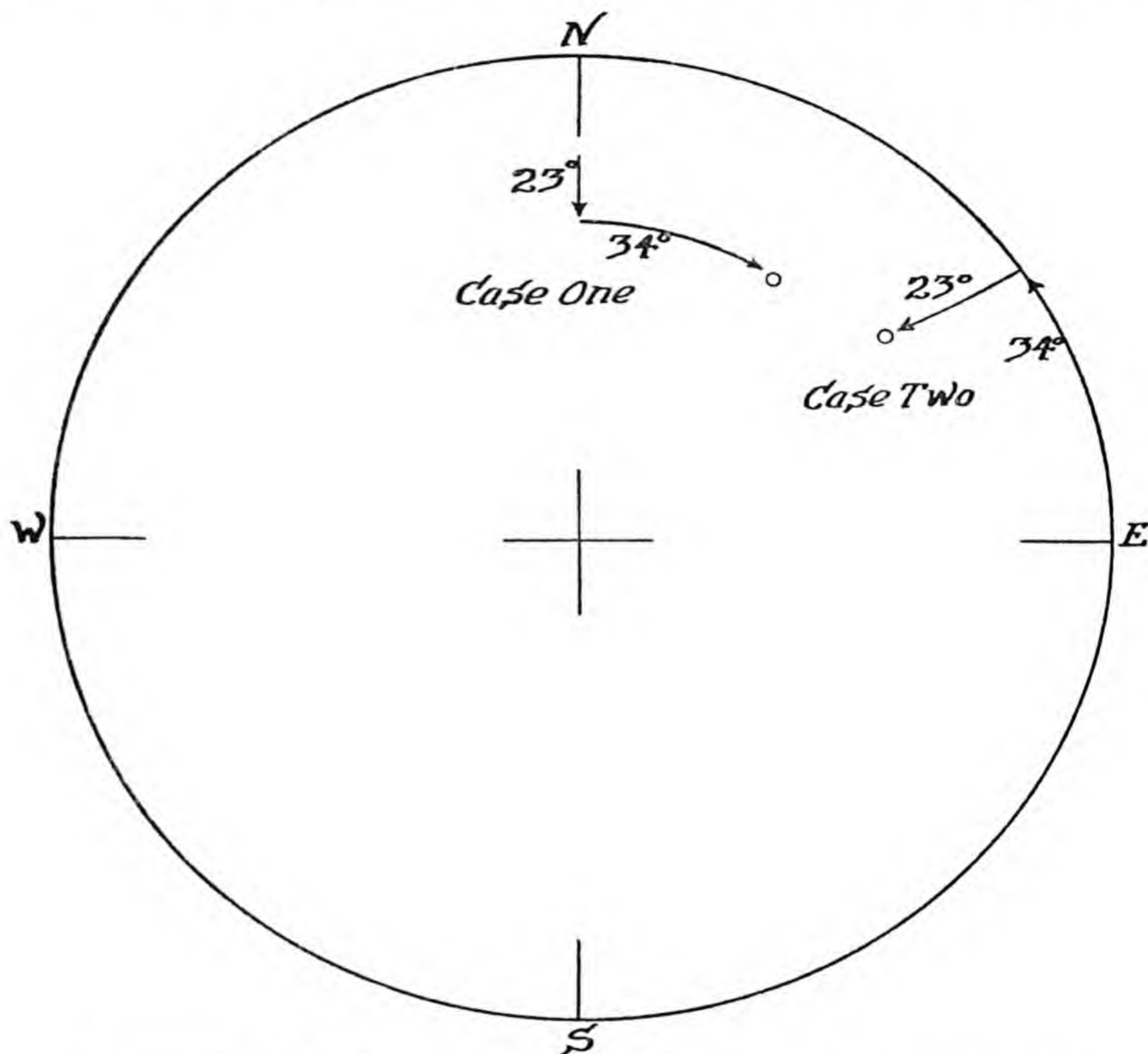
FIGURE 76.—*Location of a face pole relative to optical orientation*

As needed to determine the composition of a feldspar by the Fedorow method. In case one the face was made east-west and vertical, using the outer east-west and outer vertical axes. In case two the composition face was made north-south and vertical, using the outer vertical and north-south axes.

of cleavage or composition faces relative to these directions. Further, we have expressed our findings on a stereographic net in which α, β, and γ are the cardinal points. The position of the pole of the chosen crystallographic plane, as it lies on the stereographic net, depends on the anorthite content. The loci of the poles of various crystallographic planes with different anorthite contents are rather well known through the work of Fedorow and Nikitin and their coworkers. These curves are represented in stereographic form (Pl. 12, figs. 1-9). If

the stereographic net is superposed on the proper plate the discovered point should fall on or near a line on the plate. The line indicates the crystallographic plane selected. The point on the line indicates the anorthite content. If the feldspar is a potash variety there is a
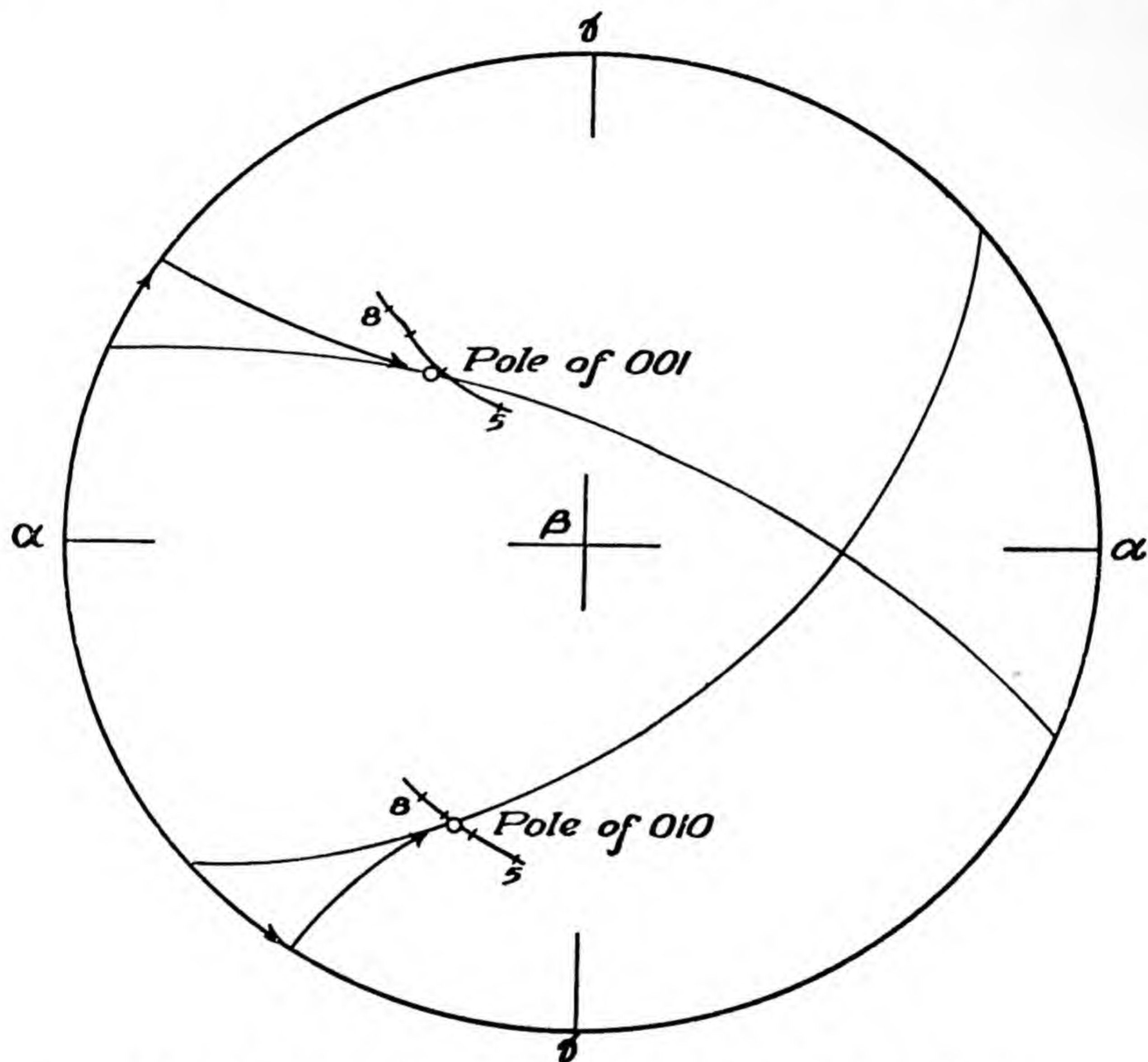
FIGURE 77.—*Stereogram of crystal in Figure 4 of Plate 7*
Plot of two composition faces for unit one. Such a plot, superposed on the proper part of Plate 12, gives the anorthite content of the crystal (Table 17).

point only, not a line to represent it according to our present knowledge.

There are four possible positions of superposition characteristic of a triclinic crystal, and each must be tried; only one is correct, and it is the one which fits best. Usually there is little doubt which one to choose. First, of course, the proper plate must be chosen—that in which the same direction (α, β, or γ) is at the center as is expressed in the stereographic net. The other two directions must of course also be made to coincide. This is the first position. Next rotate the net about the north-south line 180°—that is, invert it. All

TABLE 17—*Twin determination—modified Fedorow method*

(Figs. 59 and 80)

Specimen No. WC9A   Locality *Superior National Forest*   Rock *Duluth gabbro*
Zero Values: Mic. *216*   O. V. *91*   Mineral *Plagioclase*   Comp. *65% An*

Unit 1:   Twin Laws: *1–2 Albite*   *1–3 Acline*

I. E–W	11° N	
N–S	42.5° E	
O. A. 1	— —	
2	— —	
	2V–1	2V–2
O. V	$\langle$ 45°	(
O. E–W	54.7° S	
M	$\langle$ 43°	(

I. V$^{\cdot}$	356
α	E
β	⊥
γ	N
Bx$_a$	N
Sign	(+)
β	
2V	

Comp. Face 1	H	52.5° W
	V	$\langle$ 34.5°
2	H	51.5° W
	V	$\langle$ 56°
Cleav. Face 1	H	
	V	(
2	H	
	V	(

Unit 2:

I. E–W	37° S	
N–S	9° W	
O. A. 1	— —	
2	— —	
	2V–1	2V–2
O. V	$\langle$ 45°	(
O. E–W	54.7° N	
M	$\langle$ 48°	(

I. V.	25°
α	N
β	⊥
γ	E
Bx$_a$	E
Sign	(+)
β	
2V	

Comp. Face 1	H	
	V	(
2	H	
	V	(
Cleav. Face 1	H	
	V	(
2	H	
	V	(

Unit 3:

I. E–W	35° S	
N–S	10.5° W	
O. A. 1	— —	
2	— —	
	2V–1	2V–2
O. V	$\langle$ 45°	(
O. E–W	54.7° N	
M	$\langle$ 49°	(

I. V.	18.5°
α	N
β	⊥
γ	E
Bx$_a$	E
Sign	(+)
β	
2V	

Comp. Face 1	H	
	V	(
2	H	
	V	(
Cleav. Face 1	H	
	V	(
2	H	
	V	(

Remarks:

cardinal directions of the two are still parallel; this is the second position. To obtain the third position, invert similarly about the east-west axis. To obtain the fourth position invert again about the north-south axis. A second inversion about the east-west axis yields the initial position again.

For accuracy the rotations used above on the instrument must be corrected for difference in refractive index between the hemispheres and the crystal. The hemispheres are known. The crystal may be identified approximately by the superposition procedure outlined already, and from this approximation its mean index is learned. The mean index is used as an average since detailed indices are not known in thin-section study. The detailed method of making corrections of this type with examples has been discussed in Chapter 4.

The plotted poles will not often fall exactly on the reference lines ("migration curves") either because of inaccurate work, the potash content of the crystal, or strain in the crystal. An experienced operator can execute the steps thus far taken in a surprisingly short time.

An example will illustrate the procedure. The crystal of Figure 59 and of Figure 4 of Plate 7 has been studied by the Rittmann zone method in Chapter 7 and by the five axis method in Chapter 8. It shows four twin units, one of which (No. 4) is too narrow to be oriented optically and must be omitted here. The orientation data for the other three units are given in Table 17.

In Figure 77, the data for unit one are plotted stereographically. On a blank, α, β, and γ were added as indicated by the table. Then using a Fedorow net or the equivalent (Pl. 9) the data on the face poles as given in the last column of the table are plotted as in Figure 76. The plot thus completed is then placed over the proper plate (Pl. 12, fig. 2) to learn on which migration curves the poles fall, and where on the curves. The appropriate migration curves are here transferred to the figure. The degree of accuracy of the method is indicated by the figure for the anorthite content as derived from the two composition faces—61 and 66 per cent. The most careful optical study leads to discrepancies such as this. The determined value of 2V fits the composition 65 per cent An.

One face pole of each unit may be located leading commonly to determinations of different anorthite content for adjacent units. This difference may be more apparent than real, since strain in the crystal could account for such differences. The procedure is simple and rapid; it is as reliable as any other optical method for the purpose and can be applied to any crystal of any orientation.

The procedure already outlined has given us a determination of the anorthite content of any or all units of a twinned feldspar crystal, but we have learned nothing of the twinning laws. The twin law of a pair of lamellae may be learned from the mutual relationship of their orientations. To complete the data for this purpose add to the recordings of the respective orientations the readings for the inner vertical axis and the data on the composition face of one unit if that has not already been studied. These data, when properly correlated on a stereographic projection, reveal the twinning axis, which may be used in a manner similar to that of the pole of a crystallographic face to indicate the anorthite content of a plagioclase, thereby confirming information already obtained. It also indicates the type of twin by its attitude relative to the composition face.

The determination of plagioclase twinning by the Fedorow method is somewhat more complicated and time-consuming. Accuracy of optical orientation is essential. The universal stage with five axes of rotation eliminates considerable of the stereographic net plotting necessary with the stage having four axes of rotation. Not only does this economize the operator's time but it also leads toward greater accuracy since plotting is one of the most consistent sources of error. The procedure is as follows:

Center the twinned crystal of interest. Rotate and note extinction; wavy extinction renders results almost wholly unsatisfactory. Make a sketch of the crystal and number the various twinned units (sometimes there are several) to avoid confusion. Orient unit one (arbitrarily chosen as such) and make the necessary rotations as before to locate the poles of the composition faces present. This makes it possible then to draw the great circles representing the trace of these composition faces in the stereographic net. Orient the other units present and carefully record all readings. For each unit determine α, β, and γ directions by means of one of the accessory plates.

The stereographic net as illustrated in Plate 9 may be used for plotting points, but, since it is necessary to superpose one net on another in the course of the work, a confusion of lines may result. It is recommended therefore that one net be placed on a light table and the plotting be done on semitransparent paper placed over this. On the semitransparent paper should be a fundamental circle of the same diameter as the 90-degree circle of the net, with short lines to indicate the cardinal points and the center (Form 3). Use one such blank circle for each twin unit studied, and on it note α, β, and γ and the perpendicular to the inner stage for the adopted orientation.

Number the sheets according to the unit numbers on the free-hand sketch of the crystal already made.

Each twin unit of the crystal must be brought to the orientation *which it occupied* when unit one was oriented. Each of the points
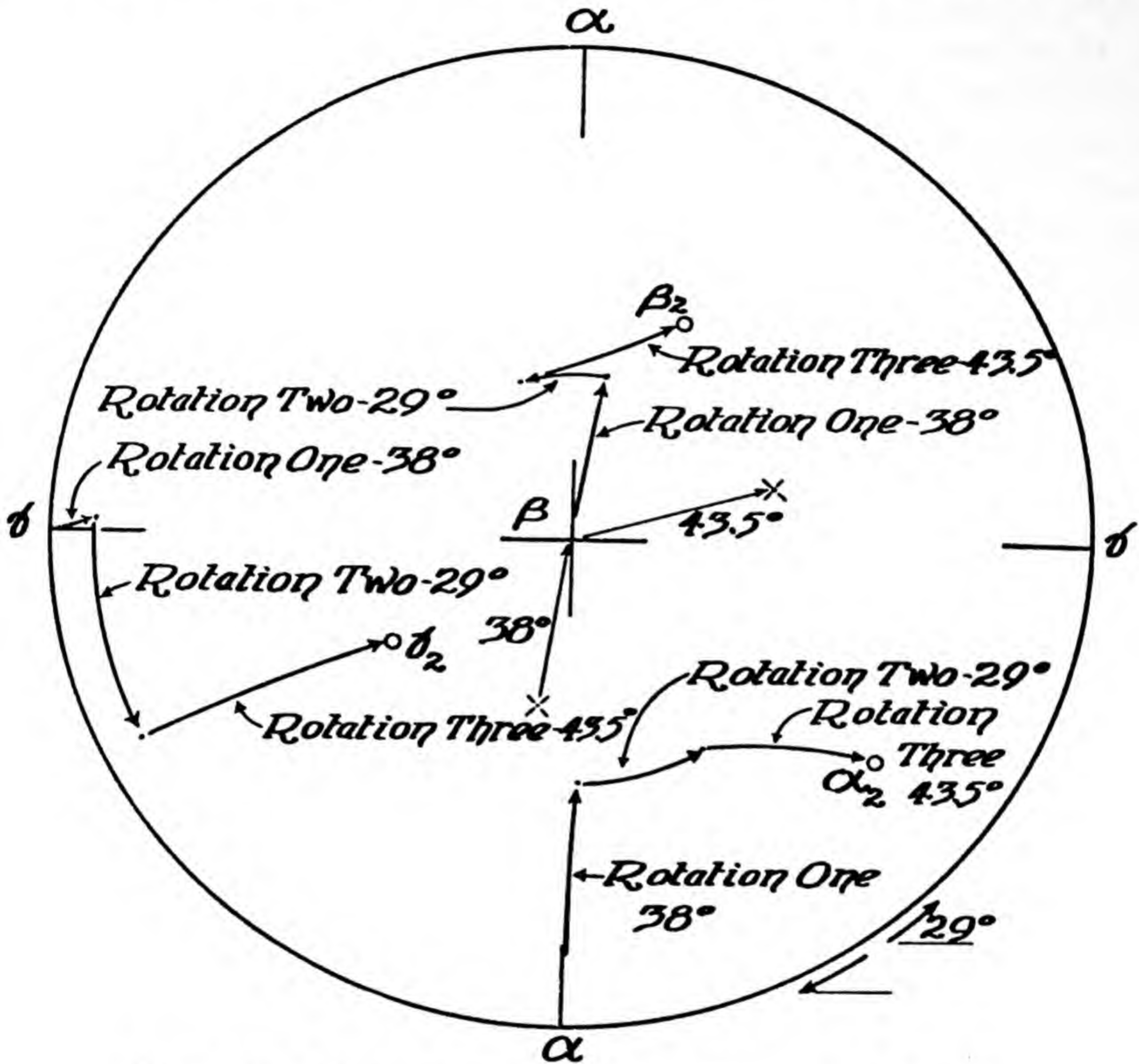
FIGURE 78.—*Stereogram of crystal in Figure 4 of Plate 7*
Procedure for the rotations of unit two to bring it to the orientation held when unit one was oriented (Table 17).

α, β, and γ for each of the units except number one is then to be moved to this new position. We are now interested in the details of these movements.

Let us consider units one, two, and three (Fig. 59). To the plot of units two and three transfer the corrected point representing the perpendicular to the inner stage for unit one. Note also the direction and angular rotation necessary to bring the inner vertical axis from its setting for units two and three to its setting for unit one. Correct the position of the perpendicular to the inner stage for units two and three. There are now three rotations to be made of the

points of units two and three. Superpose in turn the plots of units two and three on the stereographic net so that the perpendicular to the inner stage falls on the proper cardinal line. Then this point may be moved along the cardinal line to the center, indicating a rotation
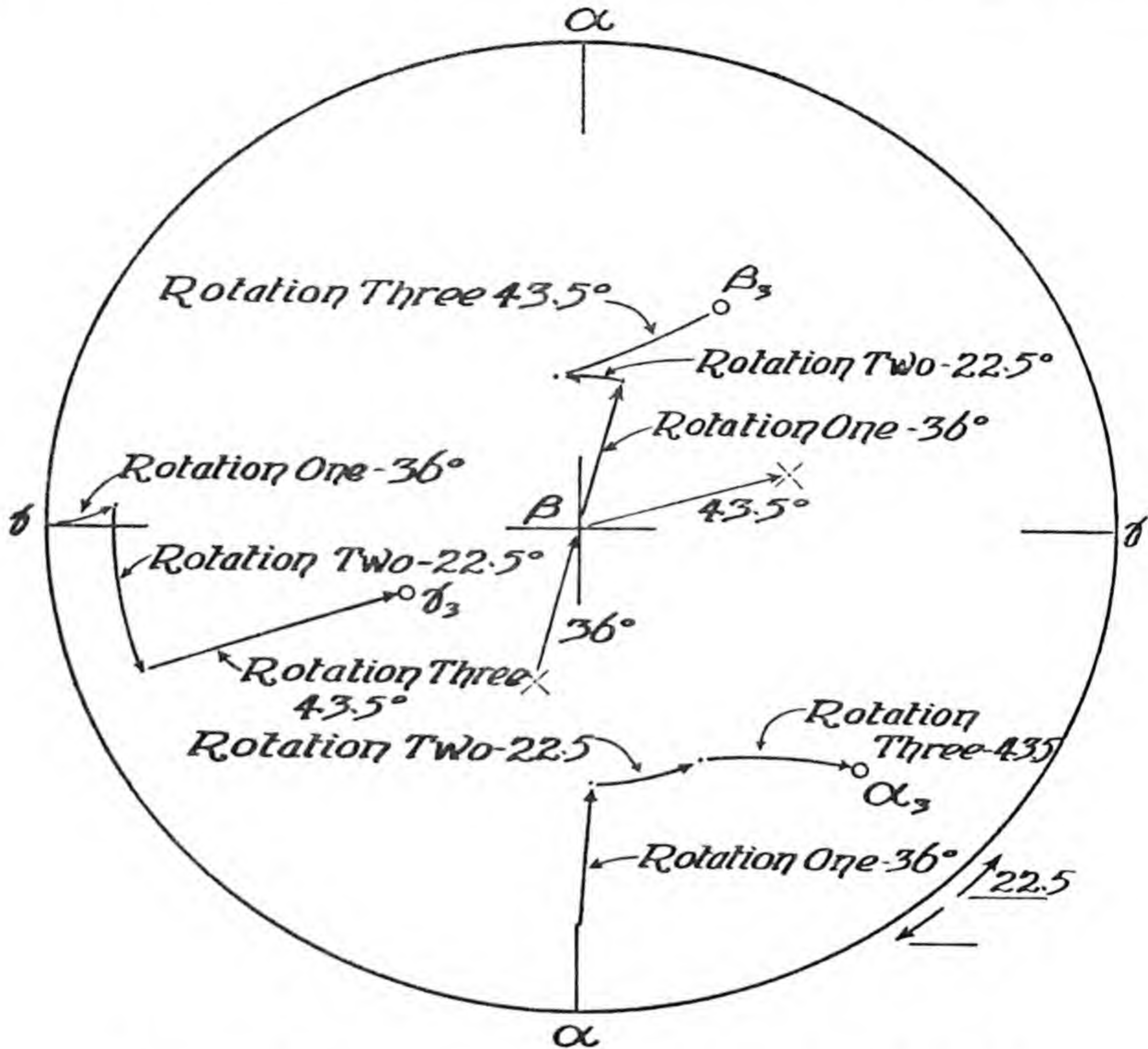
FIGURE 79.—*Stereogram of crystal in Figure 4 of Plate 7*
Operation for unit three similar to that followed for unit two (Table 17).

of that amount. Each of the points α, β, and γ may also be rotated similarly along the proper lines of the net to give the unit a new orientation—that which it occupies when the inner stage is horizontal. This is rotation one of Figures 78 and 79. Next, each point is rotated concentrically about the center the amount already noted equal to the difference between the inner vertical stage reading of this unit and unit one, and in the proper direction to make the two coincide. This is rotation two of Figures 78 and 79. Lastly, the point representing the perpendicular to the inner stage for unit one as transferred to units two and three is now placed over the proper

cardinal line of the stereographic net as was done before, and a
rotation is made to bring the center to this point and to rotate each
of the points α, β, and γ a like amount. This is rotation three of
Figures 78 and 79. Now the unit being studied is in the orientation
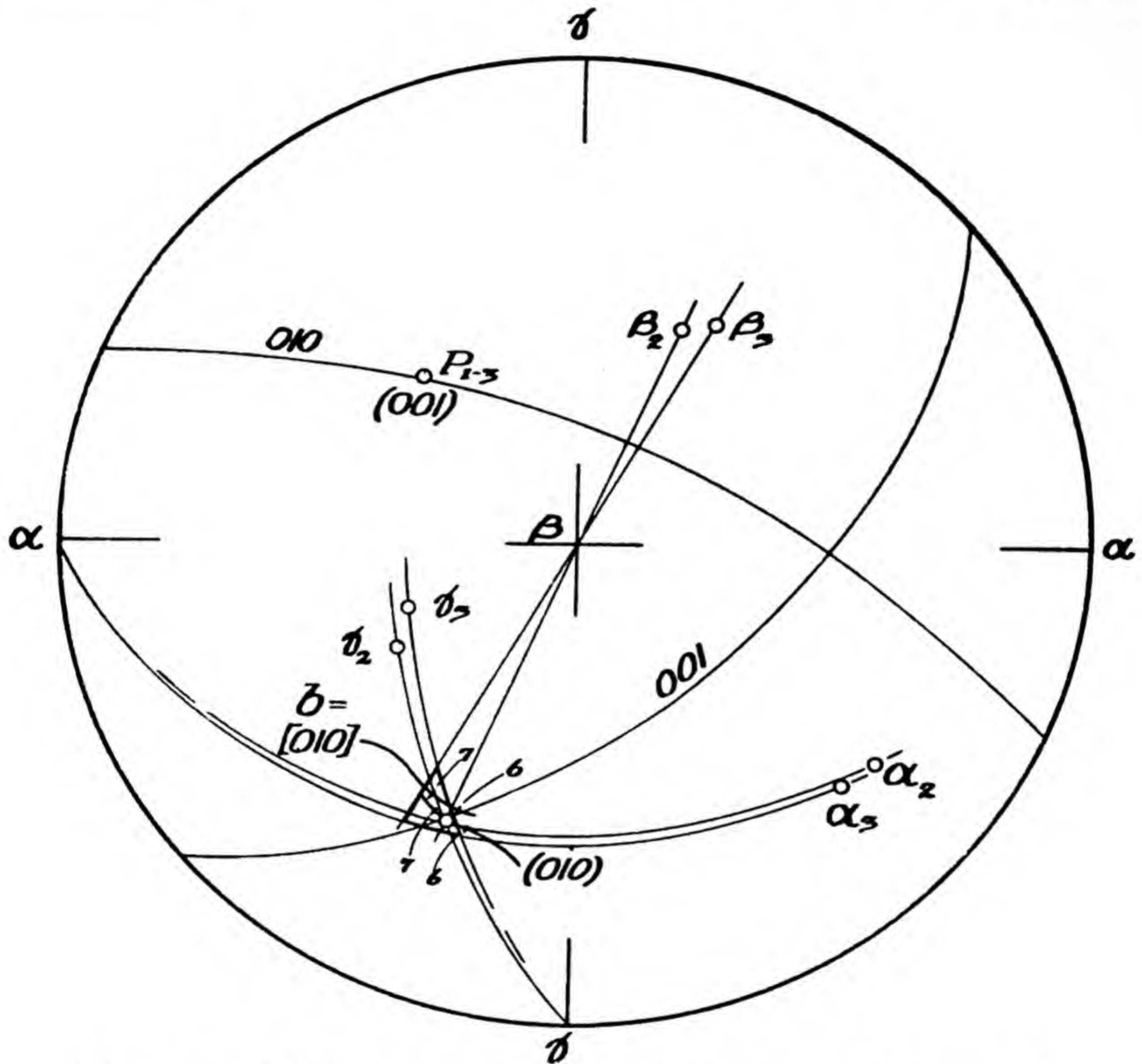
FIGURE 80.—*Compilation sheet of crystal in Figure 4 of Plate 7*

Plot of unit one. Orientations of units two and three (Figs. 78, 79) are added.
The great circles through a₁-a₂, β₁-β₂, etc., have been drawn, and the twinning
axes have been thereby located. The appropriate migration curves are also
added in part.

which it occupied when unit one was oriented. By superposing the
plot of unit one on the plot of unit two, and so on, the points α, β,
and γ of unit two are transferred to unit one in their new position
and designated $α_2$, $β_2$, and $γ_2$ (Fig. 80; *see* Table 17 for data).

Two types of net have been used for most of this graphical con-
struction—the Fedorow net shown in Figure 81 and the Wulff net
shown in Figure 82. Each has its advantages and limitations. The
Fedorow net is especially useful on account of its completeness. The
only limitation is the confusion of lines, especially when a work sheet

is superimposed on it for tracing. The Wulff net is not at all confusing but can be used for only one type of operation. The writer uses a modified Fedorow net (Pl. 9) which contains one set of great circles, one set of small circles, one set of radials, and one of con-
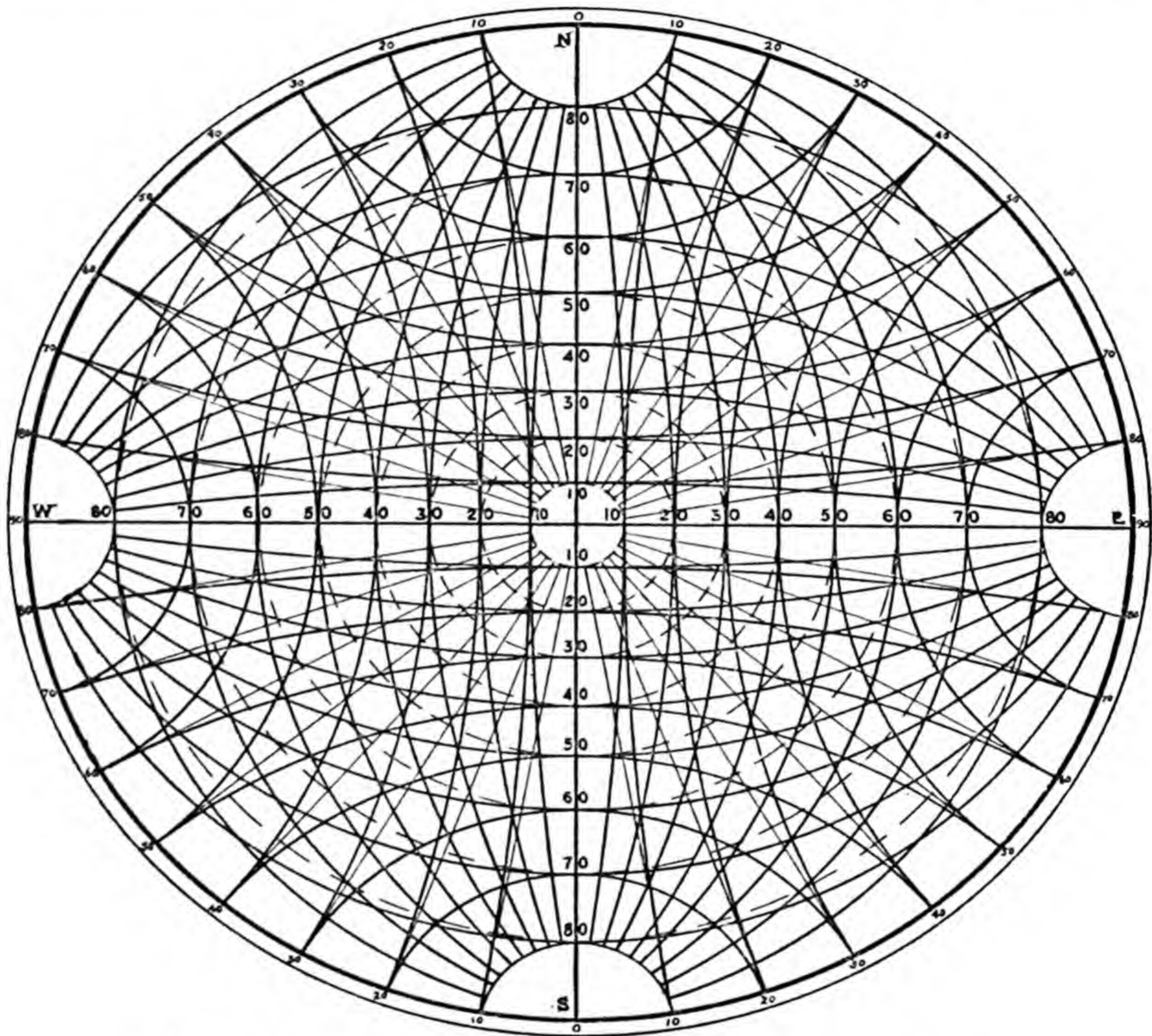
FIGURE 81.—*Original Fedorow net in 10-degree intervals*

centric circles all in 10-degree intervals. For rough work this satisfies the needs. For greater accuracy the upper half contains radials and concentric circles in 2-degree intervals, and the lower half contains great and small circles in 2-degree intervals. By inverting the net or the work sheet the entire circle can be covered in 2-degree intervals.

The twin axis may now be located. To do so superpose the plot of unit one on the stereographic net and trace the great arcs which pass through $\alpha_1 - \alpha_2$, $\beta_1 - \beta_2$, and $\gamma_1 - \gamma_2$, and $\alpha_1 - \alpha_3$, $\beta_1 - \beta_3$, and $\gamma_1 - \gamma_3$. These great arcs intersect at a point (ideally) or delimit a small triangle within which a point may be chosen. This point is the

twin axis for the two units. It is expressed in the drawing most easily as an orientation relationship with respect to the optical elements (α, β, and γ) of unit one. The frequency of strain (wavy extinction) in feldspars is emphasized by the large triangle commonly ob-
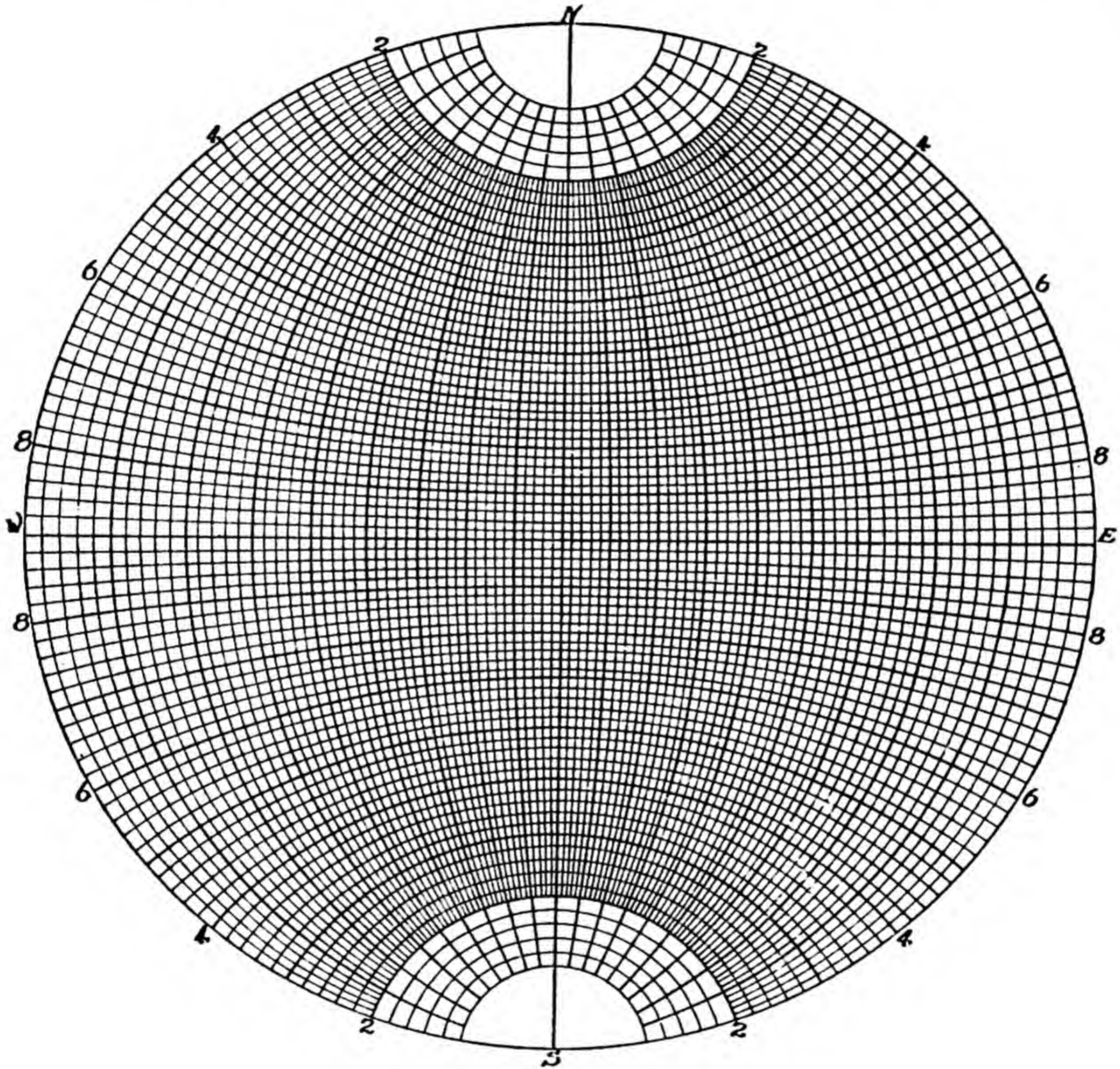
FIGURE 82.—*Wulff net*

tained. A slight error in optical orientation may lead to a very large triangle. The examples below are typical.

Other studied units (4, 5, and so on) are similarly plotted, rotated to the positions they occupied when unit one was oriented, and then transferred to unit one, and the mutual twin axes are similarly determined. Since one of the units (unit one) is oriented, it is unnecessary to rotate the now numerous points into such a position, as is required in procedures using the four-axis stage.

The following examples clarify details which may be obscure in the preceding discussion.

1: This is the same crystal used in the preceding few pages to illustrate the use of migration curves (Figs. 59, 77-79). The details may now be summarized. The data obtained on the microscope are given in Table 17. Units 2 and 3 are oriented and rotated (Figs. 78, 79), and these are then transferred to the plot of unit 1, which becomes the compilation sheet, by placing unit one sheet over
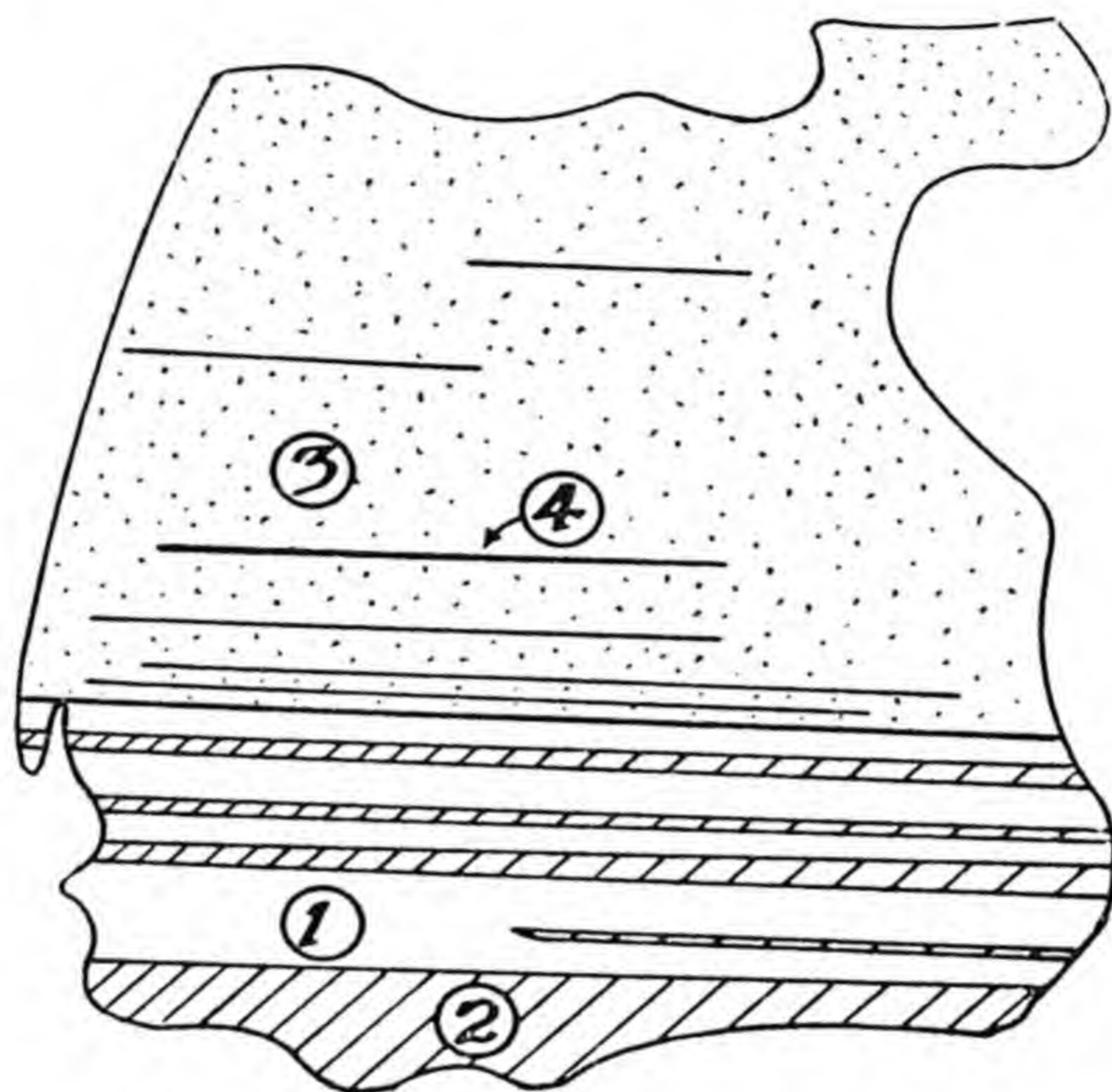
FIGURE 83.—*Key to Figure 6 of Plate 7*

each of the others on a light table and tracing through the new positions of α, β, and γ for units 2 and 3. Each is marked accordingly (Fig. 80). The twinning axes are now to be related by connecting α_1—α_2 etc. as great circles. Since, in the compilation sheet, unit one appears with α, β, and γ as cardinal points, which are also the points of origin of the great circles, by superimposing the compilation sheet on the Fedorow net (Pl. 9) the proper great circle which joins α_1—α_2 etc. may be traced through. The three circles for unit 1 and 2 together make a triangle, as do the three for units 1 and 3. In the triangle lies the twinning axis. If the pole of the composition face also lies within the triangle this point would be chosen as the twinning axis, and the twin law is thereby recognized as a normal law. If the pole is remote from the triangle (as is P_{1-3}) the composition face passes through the triangle, and the twinning axis lies on this line. The larger the triangle the more uncertainty there is about the true position of the twinning axis, and large triangles may be expected for strained crystals.

Theoretically there is a twinning axis for units 2-3, but the error is sufficient that no triangle is evident. When points occur as close together as do α_2—α_3 etc. in Figure 80, extremely high accuracy is necessary throughout. In fact, the greatest limitation of the Fedorow procedure is the almost constant demand for accuracy, to a degree that is too time-consuming for routine work where technique is not the main objective.

The completed compilation sheet is, as a last step, to be superimposed on the stereograms of Plate 12 to learn on which curves the axes fall and where on the

curves. Since β is at the center of the compilation sheet, the normal twin axis is superposed on one of the curves of Figure 2 of Plate 12. The curve which fits is (010), and the composition is 65 per cent. An. The law is the albite law. The compilation sheet is then superposed on stereogram Figure 5 of Plate 12, in the proper position to determine the law of the other twinning axis. This one we
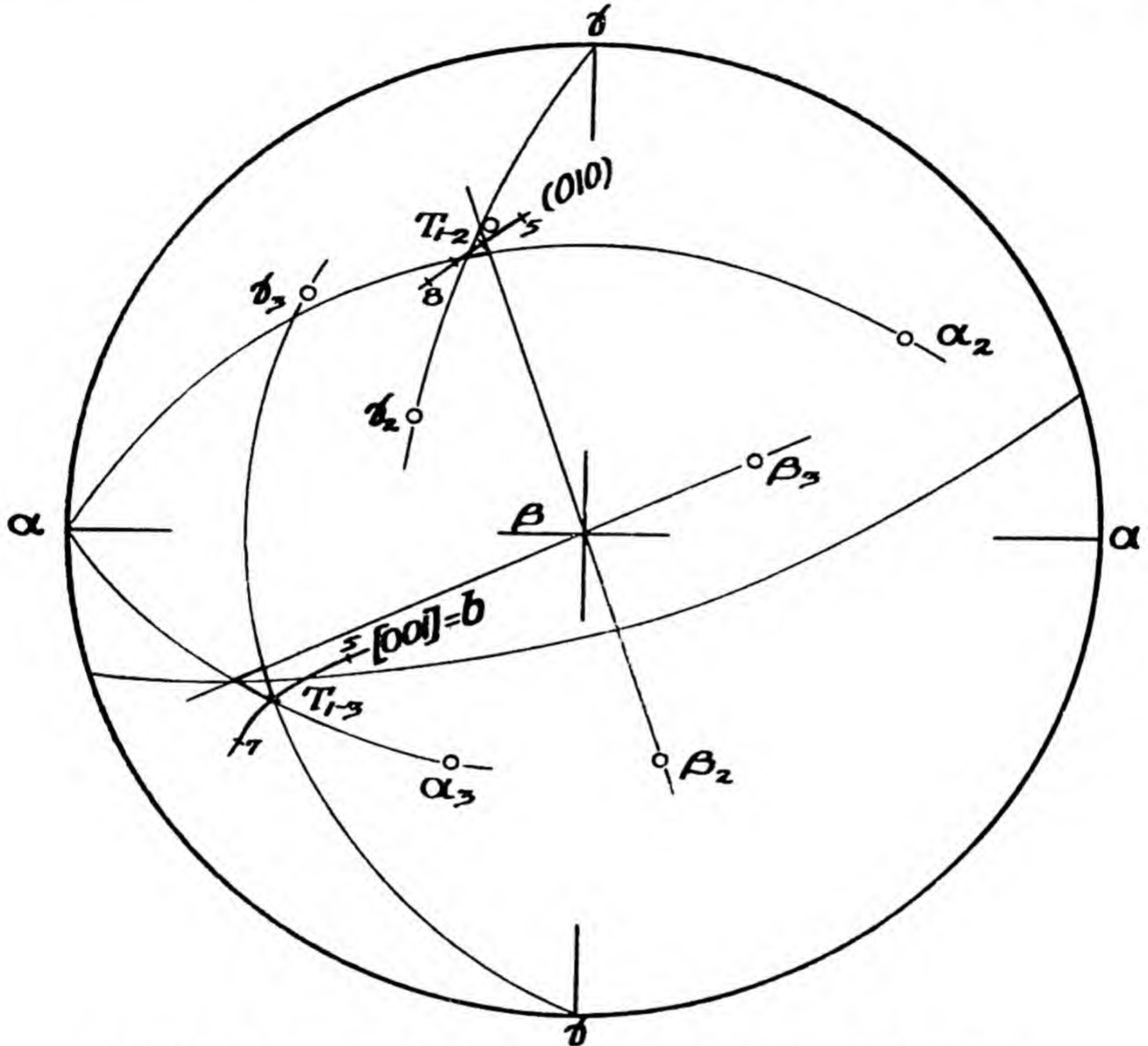
FIGURE 84.—*Compilation sheet of crystal in Figure 6 of Plate 7*

Twinning axes are located by the triangles formed by the intersecting great circles. Ordinarily the drawing is superimposed on the proper stereograms of migration curves, but here the appropriate migration curves are added to the compilation sheet (Table 18).

know to be either parallel or complex since the axis lies in the composition face. Figures 4, 5, and 6 of Plate 12 give the migration curves of parallel and complex axes only. The curve on which this axis falls is b—acline or pericline. Since the pole of this composition face was found to be (001) rather than the rhombic section the twin law is the acline law. There is some doubt of the composition, but it is indicated to be between 65 and 70 per cent. An.

2: This crystal (Fig. 83; Pl. 7, fig. 6) is one of the more common types found in rocks, of almost any plagioclase composition. Of the four twin units represented, one set is made up of lamellae too narrow for orientation and is therefore undetermined. The data are given in Table 18. As for the first example, units two and three were plotted on blank stereograms and rotated to the orientation which they

TABLE 18.—*Twin determination—modified Fedorow method*

(Figs. 83 and 84)

Specimen No. WC2A   Locality *Mellen, Wis.*   Rock *Gabbro*
Zero Values: Mic. *216*   O. V. *91*   Mineral *Plagioclase*   Comp. *55% An*
Unit 1:   Twin Laws: *Albite, Carlsbad*

I. E–W	0.5° S		I. V.	336.5°		Comp. Face 1	H	23° N
N–S	3.5° E		α	E			V	⌐17°
O. A. 1			β	⊥		2	H	
2			γ	N			V	(
	2V–1	2V–2	Bxₐ			Cleav. Face 1	H	
O. V	⌐45°	(	Sign				V	(
O. E–W	55° N		β			2	H	
M	⌐45°	(	2V				V	(

Unit 2:

I. E–W	21° S		I. V.	111°		Comp. Face 1	H	25° N
N–S	45° E		α	N			V	⌐74°
O. A. 1			β	⊥		2	H	
2			γ	E			V	(
	2V–1	2V–2	Bxₐ			Cleav. Face 1	H	
O. V	⌐45°	(	Sign				V	(
O. E–W	55° N		β			2	H	
M	⌐48°	(	2V				V	(

Unit 3:

I. E–W	15° N		I. V.	31°		Comp. Face 1	H	23° N
N–S	34° W		α	E			V	⌐17°
O. A. 1			β	⊥		2	H	
2			γ	N			V	(
	2V–1	2V–2	Bxₐ			Cleav. Face 1	H	
O. V	⌐45°	(	Sign				V	(
O. E–W	55° S		β			2	H	
M	⌐44°	(	2V				V	(

Unit 4:

I. E–W	Too narrow to		I. V.			Comp. Face 1	H	
N–S	orient.		α				V	(
O. A. 1			β			2	H	
2			γ				V	(
	2V–1	2V–2	Bxₐ			Cleav. Face 1	H	
O. V	(	(	Sign				V	(
O. E–W			β			2	H	
M	(	(	2V				V	(

Remarks:

held when unit one was oriented. Then they were transferred to unit one which was chosen as the compilation sheet. Unit one with its additional data is shown in Figure 84. Note especially that the triangles allow considerable room for the selection of a point for the twinning axis. By exercising more care and time a higher degree of accuracy may be obtained, but the work becomes more costly. This example also is a routine run, satisfactory however for the determination of the twin law. As brought out elsewhere, these irregularities are not always to be attributed to mere inaccuracy on the part of the operator. In fact, if the optical equipment shows no evidence of strain and if the crystal itself shows no wavy extinction there is little reason to suspect inaccuracy in the technique. Rather the reason lies in the crystal itself. On the other hand any error in the procedure becomes magnified in its effect by this method, and no carelessness can be tolerated.

In the compilation sheet (Fig. 84) are shown the two pertinent migration curves, the composition face, and its pole. The twin laws are albite and Carlsbad. There is a theoretical relationship also between units two and three which is albite-Carlsbad complex. It is better however to limit the deduced relationships to those units which are in actual contact, thereby avoiding meaningless repetition.

The large amount of time needed for the Fedorow method and the occasional discouraging results have led to the two other methods of twin determination discussed in Chapters 7 and 8.

Chapter 10

New Thin-Section Method for Determination of Birefringence

THE refractive index is recognized as a superior determinative criterion when it can be measured, but sometimes its measurement is difficult or impossible. Our highest commonly used index liquids have values a little over 1.8. The phosphorus-sulphur-methylene iodide solution announced by West (1936) gives indices over 2.0. However, refractometers suitable for immersion work read no higher than 1.84, necessitating the determination of the refractive indices of higher liquids by the minimum deviation method or the method discussed in Chapter 12. Above the range of liquids, the immersion method is carried out with "solid melts", the best of which are those of sulphur and selenium by Merwin and Larsen (1912). These have no equal, but their transparency is poor in part of the range, and their mounts must be prepared with real skill. Fortunately most of our minerals have refractive indices below 1.8. For those of higher index there is still no thoroughly satisfactory means of ready recognition by refractive index.

The original purpose of the method outlined here was to make possible a reasonably satisfactory estimate of the birefringence of a high-index crystal for use in identification (Emmons, 1937). It is intended to be applicable to crystals of birefringence as high as .30, but it is not limited to crystals of either high birefringence or high refraction. The accuracy is greater the more closely the refractive index is known. To this extent the method may be regarded as a confirmatory test. It is especially useful when one grain in a section is of interest but is unfavorably oriented or for some other reason is not recognized by "immediate" tests.

For this method the crystal grain must be in thin section; therefore if the occurrence is in a grain mount the grains must be ground to have parallel sides as in a thin section. This requirement follows the use of standard accessory plates such as the quartz wedge or Berek compensator, all of which require that the thickness of the crystal be known in measuring the retardation. In principle the method is similar to that originally designed by Fedorow in which the partial birefringence is determined for a known orientation and the total birefringence is obtained by extrapolation.

In the preparation of rock thin sections, ordinarily the borders of the slice are lost first on grinding, where the mineral grains are in general contact with the cement (balsam, usually). Elsewhere in the slide there is mutual support between rock constituents. In grinding a grain mount, where each grain is surrounded by cement there is a lack of adequate support unless the cement is strictly
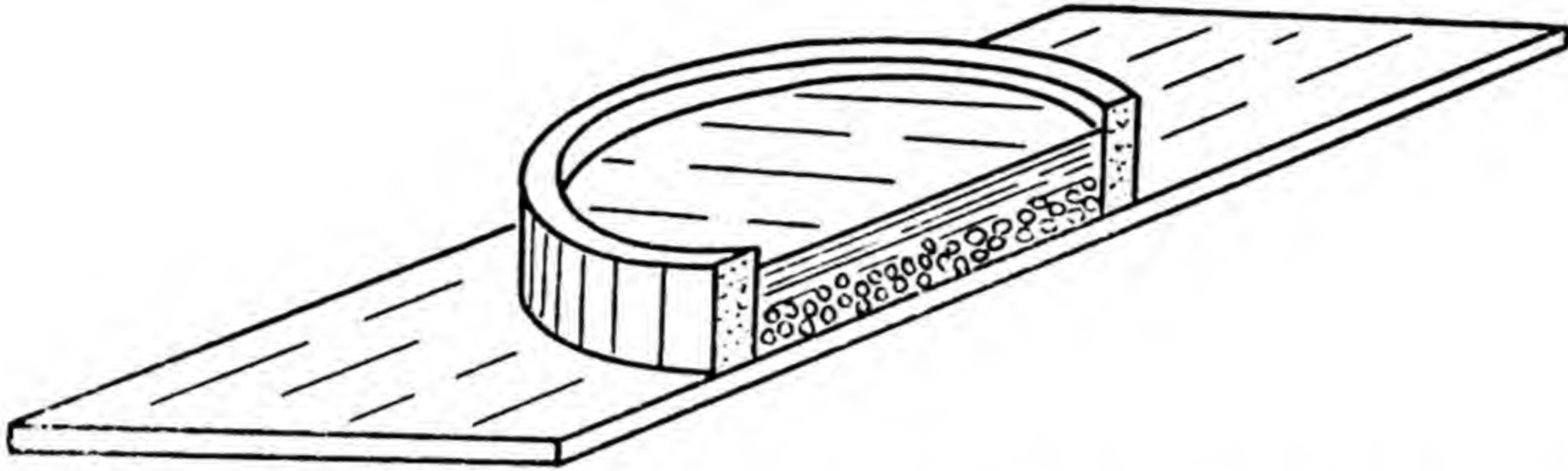

FIGURE 85.—*Preparation of balsam mount of grains to be sectioned*
(After Mamourovsky and Samsonoff)

conditioned. Therefore there is a tendency for grains to "pluck out," and the mount is no longer representative of the original sample. If balsam is used, plucking can be virtually eliminated by a skillful preparator who can heat the balsam to the correct hardness—neither too hard to become brittle nor too soft to yield to grinding pressure. A special technique has been worked out by Mamourovsky and Samsonoff (1923) which aims to overcome plucking in preparing grain mounts. Their procedure is recommended for this purpose and may profitably be summarized.

Cut quarter-inch-long sections from hard glass tubing of about quarter- to half-inch inside diameter. This is best done by means of a glass cutter which fits into and scratches the inside of the tube. A tube so scratched breaks easily when held for a moment in the flame. These sections may then be ground on a lap to smooth both ends. Place the tube section on a glass slide and the whole on a hot plate. Fill the cup so formed with hot balsam which has already been conditioned for proper hardness. Add the grains which are to compose the slide and stir if necessary to cause the grains to wet properly and sink. Remove the slide and cool it in water. At this stage the mount consists of a slide on which is a glass cup filled partly with hard balsam in the bottom of which are the grains to be ground (Fig. 85).

After the mount is chilled the cup detaches itself from the slide. If it should not do so, pass the slide through a flame a few times so as to warm it from the under side. Remove the cup of balsam from

the slide as soon as possible and before the heat passes into the cup. The grains are, of course, in one end of the cup. This end is ground on a plate or lap until the surfaces of the grains exposed satisfy the judgment of the operator. *Polishing in addition to grinding is recommended* to reduce relief within the border of grains of high index. One side of all exposed grains is now ground flat. This end of the tube is next cemented to a slide and thereby each grain will be cemented. This is the most difficult part of the procedure to do well. Failure to condition the balsam or other cement used will lead to plucking. Although the author of the method claims to have overcome plucking, the present writer has lost *some* grains near the final stage of later grinding from *all* mounts cemented with balsam.

Therefore the following modification is recommended. After grinding the grains flat on one side, since each grain is surrounded on all other sides with balsam, the cement used will not appear around the grain. Testor's cement [7] has been found superior in doing this last cementing. Apply some of this cement to the ground end of the glass tube and press it tightly to a slide. Allow to dry a few hours *under pressure* such as that of a hose clamp, and then place it in an oven at 50°C. for a day or two. By this technique most of the cement is pressed out, but each grain is cemented on its ground side to the slide. The mount is now ground down on a lap to the desired thickness as indicated by known minerals (*see below*), and a cover glass is applied. Grains so mounted have plane parallel sides as in a thin section, and the grains are surrounded by balsam only.

Although usually at least a few grains are recognizable at sight it is well to be sure that some known material is present in the mount both to serve as a sure indicator of the thickness of the slide during grinding and, more important, to serve as a means of measuring the thickness accurately on the universal stage later. With this in mind, therefore, if the material to be studied does not contain quartz, such for instance as a heavy mineral suite sample, then a few quartz grains may be added to that part of the sample chosen for a section. If quantitative microscopic studies are to be made the quartz may be ignored in the count.

If the sample is small use a small glass tube as a cup. Plucking is reduced if the grains are close together. The glass tube serves to protect the grains from the impact of grinding.

The thickness of the slide is to be determined on the universal

stage by means of the quartz grains before any unknowns are studied. For general work a few scattered quartz grains may be used and a general figure obtained for the thickness of the slide. For more careful work a grain of quartz which is rather near the unknown may well be measured and this value used as the thickness of the unknown. Only an occasional slide is of uniform thickness.

To measure the thickness by means of a quartz grain the following procedure is convenient. Place the quartz grain in that extinction position in which the optic axis is in the plane of the polarizer (the grain will remain at extinction on rotation of the outer east-west axis), turn about 45° on the microscope stage and then to extinction on the outer east-west axis. The optic axis is now parallel to the axis of the microscope. Now introduce the proper accessory plate (mica, usually, for quartz) to give the grain a known interference color (retardation 147mμ). Rotate to compensation on the outer east-west axis. Turn to Plate 13. The abscissa of the central part of the plate is the retardation, learned from the interference color, which was compensated by inclining the axis of the quartz grain. The ordinates of the central part of the plate are the unknown thickness of the grain, and the inclined lines are birefringence lines of the Michel-Lévy diagram of standard text books. The inclined lines to the left are marked in degrees of rotation of quartz. Knowing the rotation on the outer east-west axis from the optic axis, the inclined line for this value is chosen. The point of intersection of the inclined line with the abscissa value of the retardation indicate on the ordinate the thickness of the grain.

The rotation of the grain on the outer east-west axis is of course to be corrected for the index of the hemispheres as always.

The rotation to compensation must be made in the proper direction, according to standard principles. If the slow ray of the grain and that of the plate are made to coincide by the rotation of 45° on the microscope stage described above the rotation toward compensation on the outer east-west axis is not possible. First rotate to the other 45-degree position on the microscope stage and then to compensation (on O.E-W.).

The thickness as obtained from Plate 13 is correct only if the inner stage was normal to the axis of the microscope when compensation was reached; otherwise the transmitted rays are passing through the section at an angle other than normal and must traverse more of the mineral. This is the normal condition and must be corrected. Johannsen has provided a diagram for the purpose, reproduced on Plate 13 as an insert. The apparent thickness of the

grain is found on the ordinate. Follow the circle indicated by this point until it is intersected by the radial which indicates the inclination of the perpendicular to the inner stage with the axis of the microscope. From this point follow the vertical lines to the abscissa which gives the true thickness of the grain.

The statement was made above that prior to rotating the grain to compensation, the proper accessory plate is introduced to give the grain a known interference color. This is used later for unknowns as well as for quartz and may now be discussed in more detail as it is a most important step in the procedure.

Either the mica plate (retardation 147mμ) or the gypsum plate (retardation 550mμ)[8] may be used in a mineral of average or low birefringence. A small rotation to compensation is to be avoided since the extrapolation is made to 90° and the greater the extrapolation the greater the inaccuracy. Therefore choose the accessory plate needed to give a rotation of 40° or more whenever possible. If the mica plate requires too small a rotation the gypsum plate is used; for minerals of high birefringence use the quartz wedge. All these accessories are of course supplanted by either the graduated quartz wedge or the Berek compensator for both convenience and accuracy. When these are used the rotation is usually made before compensation is established.

When using either the quartz wedge or the Berek compensator a crystal of high index with a rough surface may yield changing interference colors difficult to follow. In this case start the rotation from the optic axis and maintain compensation by progressively advancing the compensator. By so doing a much larger rotation of the crystal is possible without losing the identity of the interference colors, and the larger the rotation the more satisfactory is the final figure of birefringence. Polishing after grinding in the preparation of the section eliminates the difficulty in high-index crystals. By this method the color produced by the wedge is the measure of the retardation. The color must of course be observed in a part of the field where it is not modified by another mineral and along the proper diagonal to the cross hairs. In general the crystal being studied is to be well centered, though centering is less important if the mica or gypsum accessory plate is used. A graduated quartz wedge and cap analyzer with adapters materially increase the accuracy. In fact, the graduated quartz wedge is as effective as the Berek compensator.

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[8] These are Bausch & Lomb Optical Co. figures. They approximate similar figures of other leading companies.

The Berek compensator is a convenient accessory for this procedure. It is unfortunately not so widely used in America as perhaps it merits. It consists of a calcite plate so mounted on a metal frame that when it is inserted in the accessory slot the optic
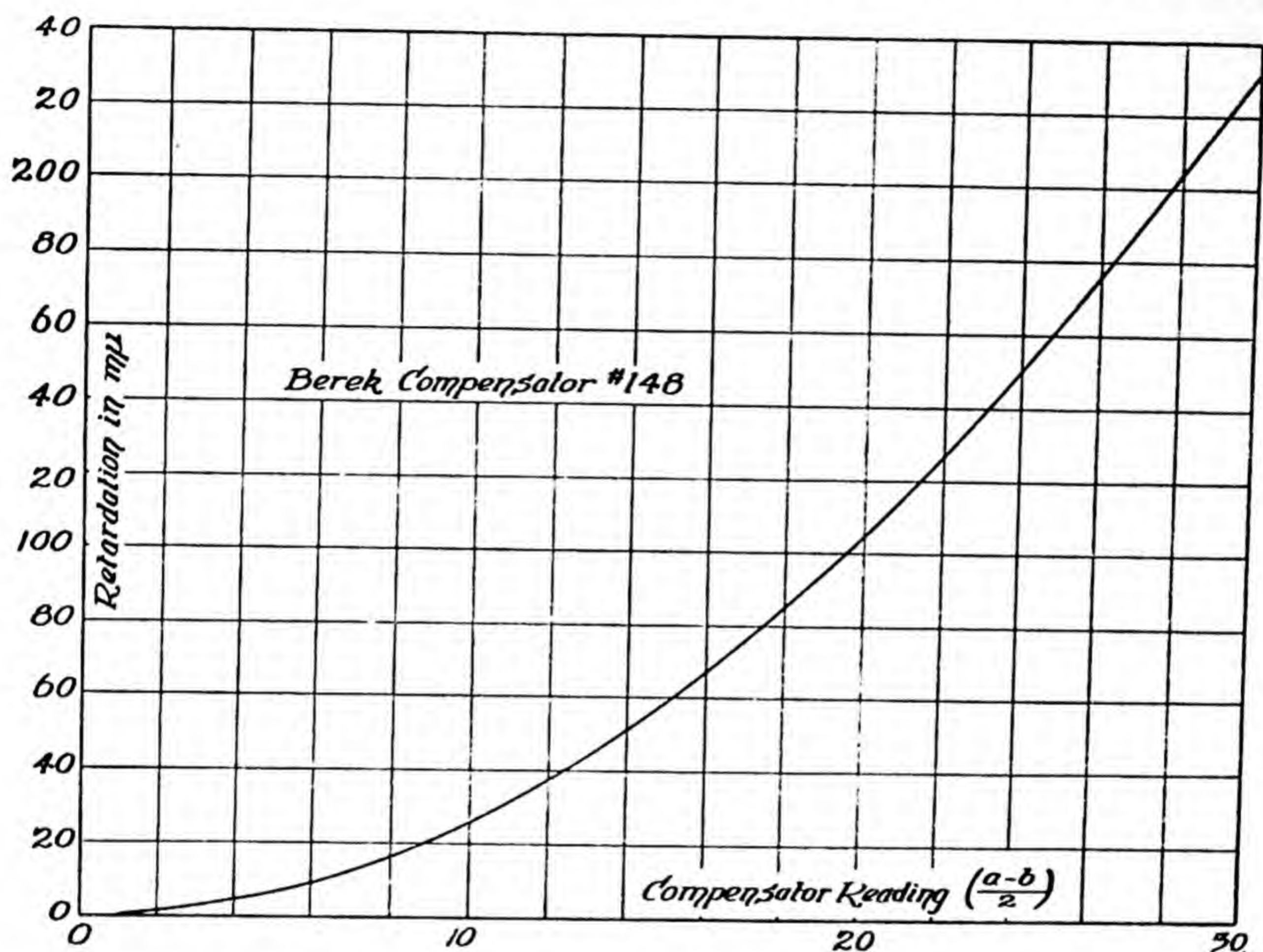

FIGURE 86.—*Curve for Berek compensator*
To facilitate its use. Each instrument must have its own curve.
Retardation figures × 10

axis of the plate is parallel to the axis of the microscope. An attached knurled thumb screw makes it possible to rotate the plate on an axis which is 45° to the cross hairs. This causes the calcite optic axis to become inclined to the axis of the microscope and in the 45-degree position to the nicols. Color rings appear as arcs in the field. A graduated drum indicates the inclination of the plate. The graduation reads from 0—60, on which scale 30 is normal or zero retardation and appears as a broad uniaxial interference figure. Identical color rings are obtained on both sides of 30.

The compensator is used as follows: A centered grain is at its 45-degree position from extinction, its fast ray coinciding with the slow ray of the compensator. The compensator is then adjusted until the black band (indicating compensation) appears at the cross hairs. If the band is not so dark at the cross hairs as it is elsewhere in the field of the grain the microscope stage is not properly

placed at 45° for the grain and should be adjusted. Still more important to watch is compensation on a small grain. If the stage is not set accurately at 45° from extinction, the position for compensation of the grain may be entirely outside the area of the grain. That is, there is apparently no compensation. To illustrate this point, in Figure 3 of Plate 6 is shown a crystal at compensation, properly centered, and in Figure 4 of Plate 6 the same crystal not quite at 45°. The compensation shadow is to be at the cross hairs when the compensator drum is read. Crystal grains which show color rings are not parallel-sided and cannot be used. The reading of the graduated drum is recorded. The drum is then rotated in the opposite direction past 30 to the corresponding position of compensation. These two positions will be almost equidistant from 30 on the scale. If the larger of the two readings is a and the smaller is b the compensator figure for retardation is given by the formula $\frac{a-b}{2}$. This figure is then converted into $m\mu$ of retardation on the table for the instrument. Each instrument has its own data furnished by the manufacturer. The value of retardation so found is as accurate as may be obtained by any convenient method. The writer has found it desirable to convert the compensator data into a curve (one for each instrument) (Fig. 86).

Knowing now the true thickness of the section of the unknown we are prepared to determine its birefringence. Let us assume first that the unknown is uniaxial and has been oriented by the method already described for the quartz grains. Incline the optic axis of the unknown, on the outer east-west axis at 45° to the nicols on the microscope stage, a suitable amount and determine the retardation as just outlined. Read and correct (1) the angle of rotation from the optic axis, (2) the angle between the axis of the microscope and the perpendicular to the inner stage at the position of compensation. The correction to both these angles depends of course on the refractive index of the unknown which must be estimated if possible. The first determination of birefringence is therefore tentative but usually identifies the unknown. This identification tells us the approximate ·index, which value is used in a second correction. The second determination of birefringence on the chart is then final. Or the method of Nikitin may be used, as described in Chapter 12, to learn the refractive index. The value of the second angle is used on Johannsen's diagram (insert on Pl. 13) to convert the *true* thickness to the *apparent* thickness for the position of compensation. This *apparent* thickness, the corrected angle of rotation,

and the measured retardation are used on Plate 13 to learn the birefringence by the following method.

On the abscissa of the central part of the diagram find the value of the measured retardation. Follow a vertical line to the ordinate value of the *apparent* thickness. From the point so located follow the inclined line *either* to the abscissa value 30mμ *or* to the abscissa value 100mμ. If the crystal is of high birefringence it will be necessary to use 100mμ and if of moderate birefringence it will be better to use 30mμ. The left-hand part of the diagram is calculated for 30mμ, and the right-hand part for 100mμ. Turn next to that part of the diagram which has been chosen, using the value for thickness which was found by following an inclined line to 30 or 100mμ. On the abscissa of this part of the diagram find the value of the rotation which was made from the optic axis of the unknown to compensation, corrected. Follow vertically to the intersection of this value with the thickness (at 30 or 100mμ). The curves indicate the total birefringence of the crystal.

There are two sets of curves; the solid-line curves are designated "index decrease," and the broken-line curves are designated "index increase." If the crystal is positive a rotation from the optic axis such as that employed here will result in an increase in the refractive index of the variable ray, and the broken line curve will be used, and vice versa for a negative crystal. In practice this means that *an index increase results if compensation is obtained when the outer east-west axis is parallel to the slow ray of the accessory plate, and vice versa.* The slow ray of the Berek compensator vibrates parallel to the length of the accessory mount.

Plate 13 as described requires that the optic axis be made vertical during the procedure. If it is not possible to do so, but is possible to make the optic axis horizontal, the birefringence may be read directly by standard methods. Or if the birefringence or thickness is too great for the application of standard methods the crystal may be rotated from the horizontal optic-axis position until the retardation can be read. Then the complement of the rotation (corrected) may be used in exactly the same way.

It is preferable always to measure the birefringence directly if the crystal can be favorably oriented and if the thickness of the section and the birefringence of the crystal permit. Only when these circumstances are unfavorable is this procedure useful. Its greatest usefulness therefore lies in studying crystals of more than moderate birefringence. Table 19 illustrates a uniaxial crystal having such high birefringence that in an ordinary section it causes more retarda-

TABLE 19.—*Birefringence determination*

(Fig. 87)

Zero Values: Microscope Stage *36°* O. V. Axis *91°*
Sample Data *M133* Hemispheres *1.559*
Bif. = *.20* Mineral *Dolomite* Quartz:

I. E–W	— —		Bx to O. A	42° S		O. A.	5°W	
N–S	— —		V–Cor't'd	38.5°		Cor.	Horizontal	
O. A. 1	42° S		O. A to Com	43° N		Comp ∠		
2			Rot Cor	39.5°		Cor.		
	2V–1	2V–2	Comp Sign	(−)		Rot.		
O. V	(	(	Ber. C	60.0	0 4	Ber. C	20 9	39.5
O. E–W			Ret	227mμ		Ret.	22mμ	
M	(	(	M′ at C	.025mm		M′ at C		
2V			γ − α	.20		M	.025mm	

tion than any standard compensator can equal, unless the optic axis is rather steeply inclined. Such crystals, unless carefully polished when the thin section is made, yield interference colors difficult to follow beyond the first order. In this example the crystal was oriented to make the optic axis vertical. Then the Berek compensator was adjusted as the crystal was rotated from the optic-axis position. Both rotations ceased when the compensator reached its maximum (60.0). The stage was inclined only 1° at compensation; therefore the true thickness (M) is also the apparent thickness (M′). The use of these data is illustrated in Figure 87.

We assumed first that the unknown was uniaxial. Let us next assume that it is biaxial. Orient the crystal and identify the optic plane. Rotate to the optic axis and thereby determine and correct V. From the optic axis rotate further in the optic plane or if V is large rotate back toward the bisectrix of the original orientation. In either position determine the retardation by compensation as described for uniaxial crystals and determine the apparent thickness by Johannsen's diagram. As for uniaxial crystals note whether the rotation from the optic axis resulted in an index increase or an index decrease.

There are only some slight changes in the use of Plate 13. Follow through as for uniaxial crystals until the value is chosen on the abscissa of the left-hand or right-hand part of the diagram for the

rotation (corrected) made from the optic axis to the position in which the retardation was measured. Next, instead of following vertically, follow the curved lines to the intersection with the ordinate value of V. From this point follow vertically as for a uniaxial crystal
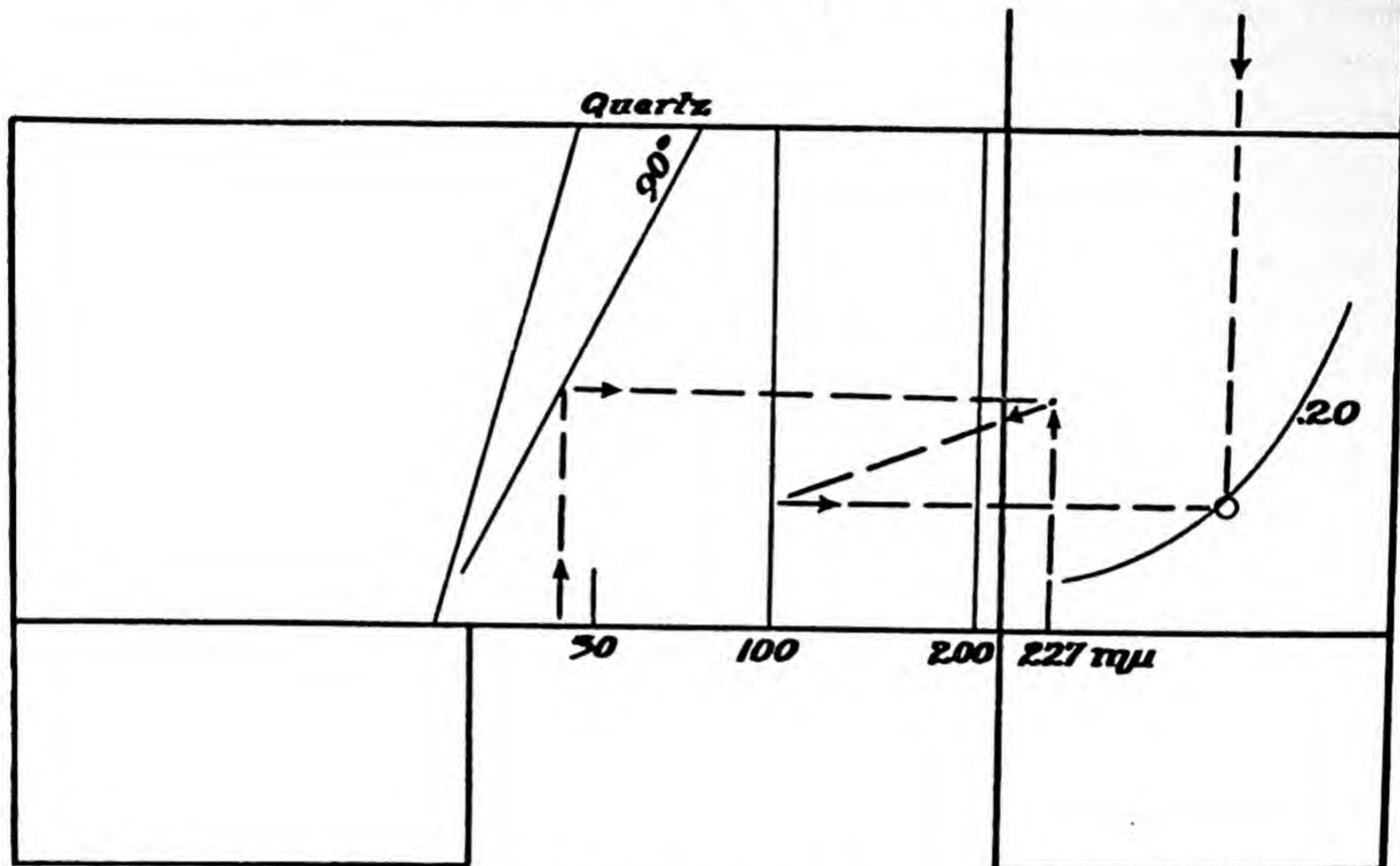

FIGURE 87.—*Use of birefringence diagram (Plate 13)*
As required by the data of Table 19
Retardation figures × 10

to the chosen value for the thickness and read the birefringence from the curves.

In using the value for V on the proper part of the diagram observe this precaution: A rotation was made to the optic axis from a bisectrix to determine V. If a further rotation was made, in which position the retardation was measured, this value of V is used. If, however, as was suggested, for a large value of V the alternative rotation was made back to or toward the same bisectrix, the complement of V is used. The microscope stage is set in positions 90° apart for these two compensation readings since the sign of compensation is reversed on opposite sides of the optic axis.

As for uniaxial crystals, measure the birefringence directly if the optic normal can be made parallel to the axis of the microscope and if the thickness and optics of the crystal permit. This procedure is designed for and requires that an optic axis can be made parallel to the axis of the microscope during the procedure. It is mainly useful in biaxial crystals of more than moderate birefringence and

in those crystals in which the optic normal cannot be made parallel to the axis of the microscope.

The right-hand part of the diagram must be followed through twice for biaxial crystals. A preliminary determination of the birefringence is needed to indicated which curve is to be followed in employing the value for V.

A very minor correction, of more theoretical than practical interest, is inserted on the plate. It is the same correction given on Plate 10b and is used only when both birefringence and refractive index are high. However, the size of this correction is less than the inevitable error involved in making the correction for such crystals for the difference between their refractive indices and those of the hemispheres.

This method is much more accurate for crystals of low birefringence than for those of high birefringence. This fortunately coincides with the need for accuracy in these respective cases since the scarcity of crystals of very high birefringence renders accuracy unessential for determinative purposes, and our prime objective here is determination.

Some examples of biaxial crystals will be given.

TABLE 20.—*Birefringence determination*

(Fig. 88)

Zero Values: Microscope Stage *36°*   O. V. Axis *91°*
Sample Data *Basalt-Copper Falls, Wis.*   Hemispheres *1.649*
Bif. = *.030*   Mineral *Hornblende*

Quartz:

I. E-W	34° N		Bx to O. A	49° S		O. A.	54.4° N
N-S	32° E		V-Cor't'd	"		Cor.	60° N
O. A. 1	49° S		O. A to Com	49° N		Comp ∠	25° S
2			Rot Cor	"		Cor.	26.5° S
	2V-1	2V-2	Comp Sign	(−)		Rot.	86.5°
O. V	(	(	Ber C	46.5 | 15.8		Ber. C	20.5 | 40.5
O. E-W			Ret	62mμ		Ret.	26mμ
M	(	(	M' at C	.038		M' at C	.029
2V			γ − α	.030		M	.027

1. (Form 5 in Table 20). The column for quartz is filled out first to learn the section thickness. The first four figures refer to (1) the setting of the outer east-west axis for the optic axis (O.A.), (2) this value corrected for the index of the hemispheres, (3) the reading at which the retardation was compensated (Comp 25°S), and (4) this value corrected. Next is (Rot.) the angle of rotation, in this case 60 + 26.5. "Ber C" is the reading for the Berek compensator, "Ret"

this value converted in Figure 86 to retardation in mμ. "M' at C" is the apparent thickness at the setting at which the retardation was measured, read from the quartz curves in the central part of Plate 13. M is the true thickness after converting M' on Johannsen's diagram.

In the left-hand column are standard orientation data. The lower part of this column cannot be used on crystals of high index because of the inaccuracies of corrections.
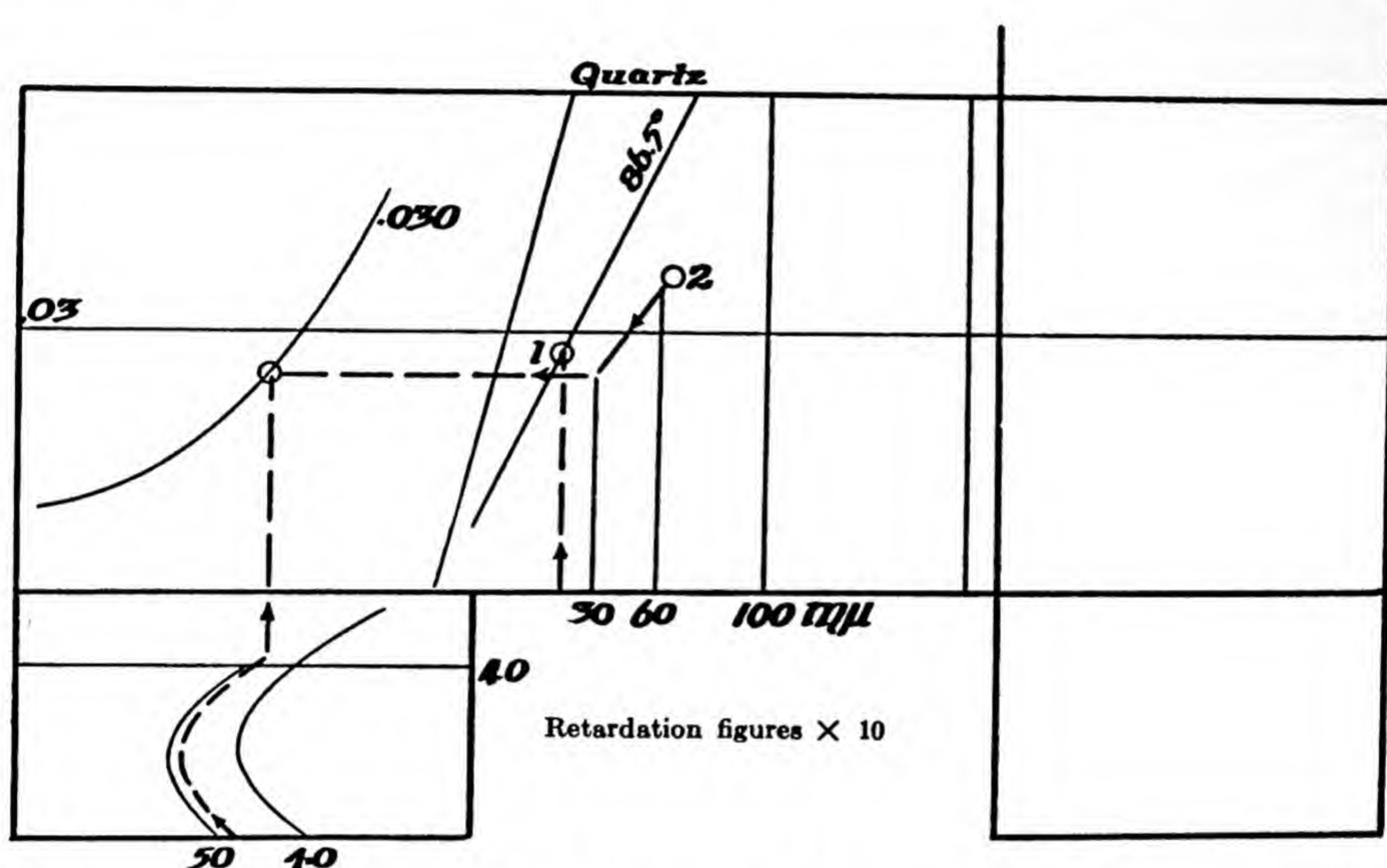

FIGURE 88.—*Use of birefringence diagram (Plate 13)*
As required by the data of Table 20. Point "1" is M' at compensation for quartz. Point "2" is M' at compensation for the unknown.

The second column is for data for the unknown, corresponding to the data for quartz in the third column. The last figure in this column is found from Johannsen's diagram using the values .027 of the third column and the angle between the microscope axis and the perpendicular to the inner stage at the position in which the retardation was measured.

On Plate 13 the values now to be used are 62 mμ retardation, .088mm. thickness, 49°rotation, and the complement of this, 41°. The compensation sign is negative. The use of these values on the diagram is represented in Figure 88.

2. (Table 21). This crystal makes it possible to compare the results when there is a choice between rotations after the crystal is oriented and the optic axis found. It is recalled that from an optic axis the rotation to the point where compensation is measured may be made either back to the bisectrix originally made vertical, in which case the complement of V is used, or on beyond the optic axis in which case the measured V is used. The choice depends on the mechanical condition. In this case both rotations are made. The thickness as learned from quartz grains is .036 mm.

From the oriented position a rotation was made 42°N to an optic axis. Then a rotation was made back 30°S. (42°S would have been equally good.) In the

second case a further rotation of 34°N was made. In the second case $\vee = 42°$ corrected to 38°. In the first case the complement 52° is used since the rotation was made back toward the bisectrix first oriented.

Note that one value of birefringence is .021, the other .019. This is consistent with the accuracy to be expected.

TABLE 21.—*Birefringence determination*

Zero Values: Microscope Stage *36°*   O. V. Axis *91°*
Sample Data *CF #5*   Hemispheres *1.559*
Bif. = *.020*   Mineral *Cyanite*   Quartz:

I. E–W	39° S			Bx to O. A	42° N		O. A.	51.5° S
N–S	21° E			V–Cor't'd	38° (52°)		Cor.	52°
O. A. 1	42° N			O. A to Com	30° S		Comp ∠	40° N
2	— —			Rot Cor	27°		Cor.	40.5°
	2V–1	2V–2		Comp Sign	(+)		Rot.	87.5°
O. V	(	(		Ber. C	40.9 | 19.2		Ber. C	42.6 | 17.7
O. E–W				Ret	31mμ		Ret.	41mμ
M	(	(		M' at C	.041mm		M' at C	.046mm
2V				γ – α	.021		M	.036mm

Bif. =   Mineral   Quartz:

I. E–W	39° S			Bx to O. A.	42° N		O. A.	
N–S	21° E			V–Cor't'd	38°		Cor.	
O. A. 1	42° N			O. A to Com	34° N		Comp ∠	
2	— —			Rot Cor	30.5°		Cor.	
	2V–1	2V–2		Comp Sign	(−)		Rot.	
O. V	(	(		Ber C	42.0 | 17.9		Ber, C	
O. E–W				Ret'n	38mμ		Ret.	
M	(	(		M' at C	.044mm		M' at C	
2V				γ – α	.019		M	

8. (Table 22). In this example are given two steps which are especially standard: (1) The quartz crystal was so oriented that the optic axis was horizontal. (2) The rotation for compensation in the unknown was made back the full amount to the bisectrix. In Examples 1 and 2 this was avoided for purposes of illustration.

4. (Table 23). This illustrates some of the difficulties encountered in higher index crystals. A higher hemisphere was used making a correction necessary in

TABLE 22.—*Birefringence determination*

Zero Values: Microscope Stage *36°*   O. V. Axis *91°*
Sample Data *4305NM*   Hemispheres *1.559*
Bif. = *.034*   Mineral *Epidote*   Quartz:

I. E-W	15.5° N		Bx to O. A	42° S		O. A.	15° W	
N-S	24° E		V-Cor't'd	37.5° (52.5)		Cor.	Horizontal	
O. A. 1	42° S		O. A to Com	42° N		Comp ∠	15°	
2			Rot Cor	37.5°		Cor.		
	2V-1	2V-2	Comp Sign	(+)		Rot.	90°	
O. V	(	(	Ber C	15.1	44.9	Ber. C	42.5	17.9
O. E-W			Ret	59mµ		Ret.	40mµ	
M	(	(	M' at C	.048mm		M' at C	.045mm	
2V			γ−α	.034		M	.044mm	

the compensation angle (19.8°) for quartz (to 20.9°) before it is used to determine the true thickness (.025mm.) from the apparent thickness (.027mm.).

In orienting this crystal, interference figures were used as they may be helpful on crystals of high birefringence and high refractive index, especially in the last

TABLE 23.—*Birefringence determination*

Zero Values: Microscope Stage *36°*   O. V. Axis *90°*
Sample Data *North Crosby Township, Ont.*   Hemispheres *1.649*
Bif. = *.140*   Mineral *(Titanite) Sphene*   Quartz:

I. E-W	14.5° N		Bx to O. A	16° S		O. A.	19.3° W	
N-S	24° W		V-Cor't'd	13°		Cor.	Horizontal	
O. A. 1	16° S		O. A to Com	49.5° S		Comp ∠	19.3°	
2	18° N		Rot Cor	28° (41-13)		Cor.	20.9°	
	2V-1	2V-2	Comp Sign	(+)		Rot.	90°	
O. V	(	(	Ber. C	4.3	55.6	Ber. C	20.4	39.5
O. E-W			Ret	172mµ		Ret.	23mµ	
M	(	(	M' at C	.033+mm		M' at C	.027mm	
2V			γ−α	.140		M	.025mm	

stages of orientation. This was done in white light. The two values of V agree after correction—the effect of the inclined dispersion of sphene was not evident.

After orientation and rotation 16°S to the optic axis, a further rotation was made to 49.5° from the acute bisectrix, for compensation. The retardation of 172mµ is great enough to require the use of the right-hand side of Plate 18. By interpolation between the dashed curves .10 and .15 the value of .14 is estimated.

Chapter 11
Universal Stage As a Refractometer

A UNIAXIAL crystal, so mounted on the universal stage that its principal section is vertical and north-south (*i. e.*, the optic axis is perpendicular to the east-west axes of the stage) will change in refractive index when rotated on the outer east-west axis. The change will be from ω when the optic axis is parallel to the axis of the microscope, to ε when the optic axis is perpendicular to the axis of the microscope. If, therefore, we use a crystal of known refractive indices and reverse the common procedure—namely, use the crystal as something of known value instead of the liquid—we may by the immersion method determine the refractive index of an unknown liquid. The range of refractive index change covered by the procedure depends then upon the birefringence of the crystal.

The uniaxial carbonates have unusually high birefringence. Calcite, for example, ranges from 1.49—(ε) to 1.65+(ω). Smithsonite ranges from 1.63—(ε) to 1.85+(ω). Both of these minerals are available in good clear form and are insoluble in ordinary liquid immersion media. The total range in refractive index afforded by these two (1.49—1.85) covers the entire range of the media commonly used. Furthermore, the standard Abbé refractometer reads only to 1.70 or 1.71 according to the make. The high index range may be covered by a special Abbé refractometer reading to 1.84 but for ordinary purposes may be covered by the method suggested here (Emmons and Williams, 1934).

Make a mount of one of these crystals on the universal stage in a liquid of which the index is to be measured. Rotate the crystal until the index of the crystal and liquid agree as indicated by the Becke line and use this rotation value on Figure 90 (the graph for smithsonite alone is given here) to learn the index. The accuracy is not greater than ±.001, but this is usually adequate for the higher indices and for some purposes is adequate for the more common indices.

For the "standard" index range (up to 1.70) the Abbé refractometer is preferred. For the higher index range there are certain advantages in this technique over the Abbé refractometer. The high index Abbé refractometer has a lead glass prism which scratches easily and which reacts with the free iodine of the liquids used to form a lead iodide coating. Both of these limitations obscure the readings and reduce the accuracy of the instrument. Another limitation of the Abbé re-

fractometer is that it fails entirely on highly colored liquids (and high index liquids are quite apt to be colored), because the rays which define the border of the light half of the field are rays of grazing incidence on the upper prism. These light rays therefore must pass through the layer of liquid in its long dimension with consequent absorption. By the method described here the longest light path
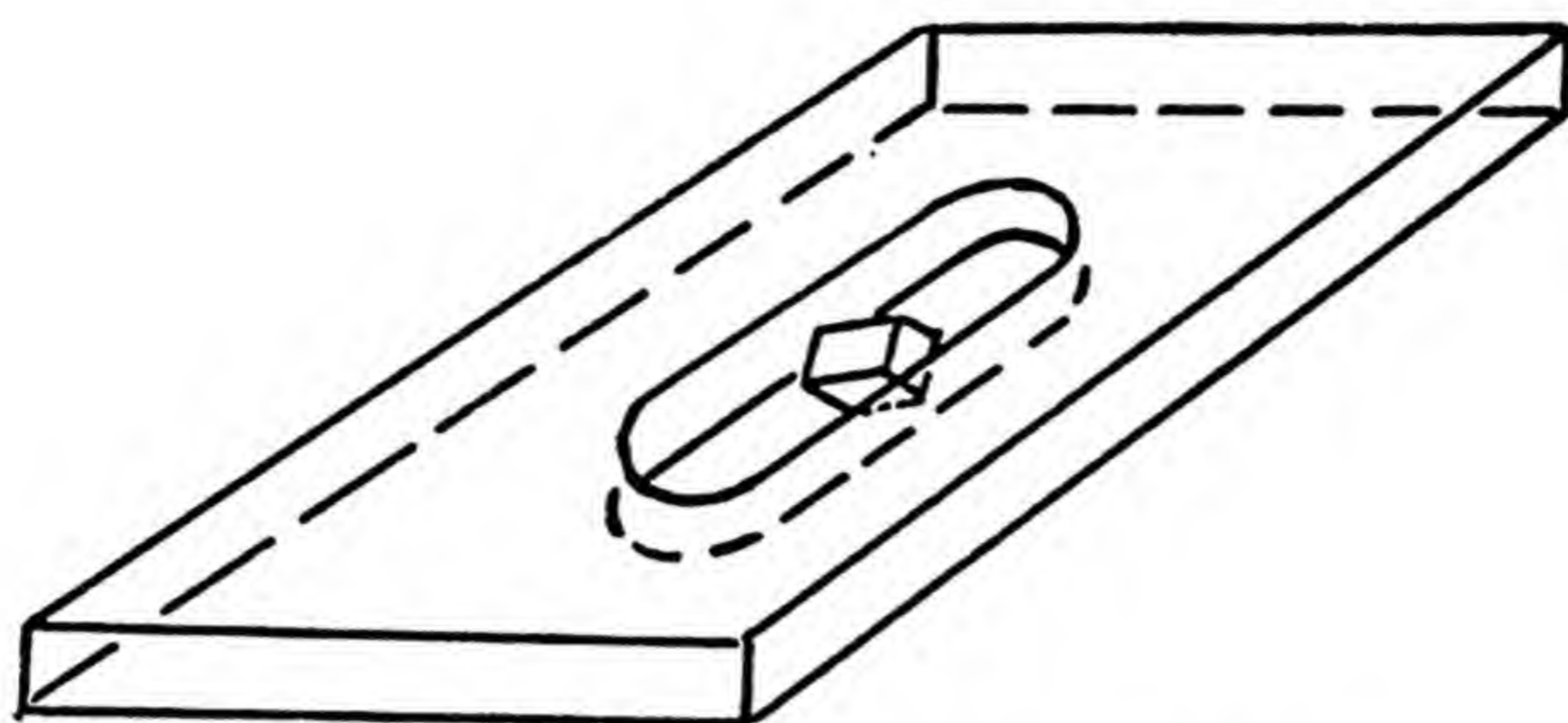

FIGURE 89.—*"Smithsonite refractometer"*

Cleavage fragment of smithsonite mounted in an opening in a glass slide for immersion in a liquid of unknown index. Refractive index of the liquid is then measured by means of the smithsonite.

through the liquid is equal to the thickness of the glass slide used. More highly colored liquids may therefore be measured here than on an Abbé refractometer.

The details of the procedure follow: A standard mount of carbonate of known optical properties may be made on a water cell as described in Chapter 5, but it is convenient to mount the crystal fragment of calcite or smithsonite in a small cell of about 5-10 drops capacity in permanent form (Fig. 89), then a few drops of liquid may be added and removed without disturbing the position of the fragment. This may be done by cutting a hole in a glass slide of standard thickness and covering one side of the opening with a cover glass cemented by water glass. To the free surface of the cover glass within the cup so formed add a very small drop of water glass in one spot. Slide a cleavage rhomb of the carbonate over to this drop so that the rhomb is cemented to the cover glass by one side only, the other sides being free to contact the immersion liquid. When the mount is dry it is ready for use. The immersion liquids do not soften the water glass cement. Water may not be used to wash the mount, but acetone is harmless to the cement and is preferred as an immersion liquid solvent. If the immersion liquid contains sulphur, as some do, carbon disulphide will remove any accumulated sulphur.

To measure the refractive index of a liquid, fill the cup with liquid, the amount required depending on the size of opening that has been cut in the slide. A meniscus will form permitting the liquid to be "heaped up"; this eliminates trapping a bubble when the cup is next covered with a cover glass. Transfer the slide now to the universal stage using a water cell and the high index hemispheres (1.649). Rotate on the inner vertical axis until the principal section is north-south as indicated by extinction, which persists on a rotation on the outer east-west axis. Remove the analyzer change to monochromatic light, and rotate on the outer east-west axis until the index of the liquid and crystal agree. This reading on the outer east-west axis is to be used on the curves (Fig. 90), modified as indicated below by the calibration for the slide.

Since the water cell is not designed to carry a slide, the two hemispheres do not make a sphere with a slide between them. To overcome this: (1) A small correction may be worked out empirically by measuring two or three liquids of known refractive index and which require different inclinations of the inner stage. (2) In the writer's laboratory a special 1.649 hemisphere is used which is thinner than standard by the thickness of a glass slide (1 mm.). This requires no correction. Or, (3) The mount may be made in the standard way and not in a prepared slide as has been suggested. This is less convenient.

The slide may next be calibrated for accuracy of construction. Be sure that the polarizer is north-south. Set the various axes at their zero positions and center the illumination with the Bertrand lens. This must be done carefully since irregular illumination will result in irregular results. Set the vertical adjustment to the customary elevation and use the same elevation consistently. Beginners are apt to center vertically the bottom of the mount at one sitting and the top at another. This is to be avoided. Make the first mount with a liquid of known refractive index, such as methylene iodide which has been checked by a reliable method, the minimum deviation method being the best. The temperature and wave length of light used should of course be properly recorded. Note the setting on the outer east-west axis at which the refractive index of the liquid and crystal agree and apply this value on the curves of Figure 90 to learn the correction factor.

The curves of Figure 90 have been constructed on a theoretical basis by measuring ω and ε for the crystal used and determining points of intermediate rotation with the help of Plate 10. Most specimens of optically satisfactory calcite and smithsonite have refractive indices
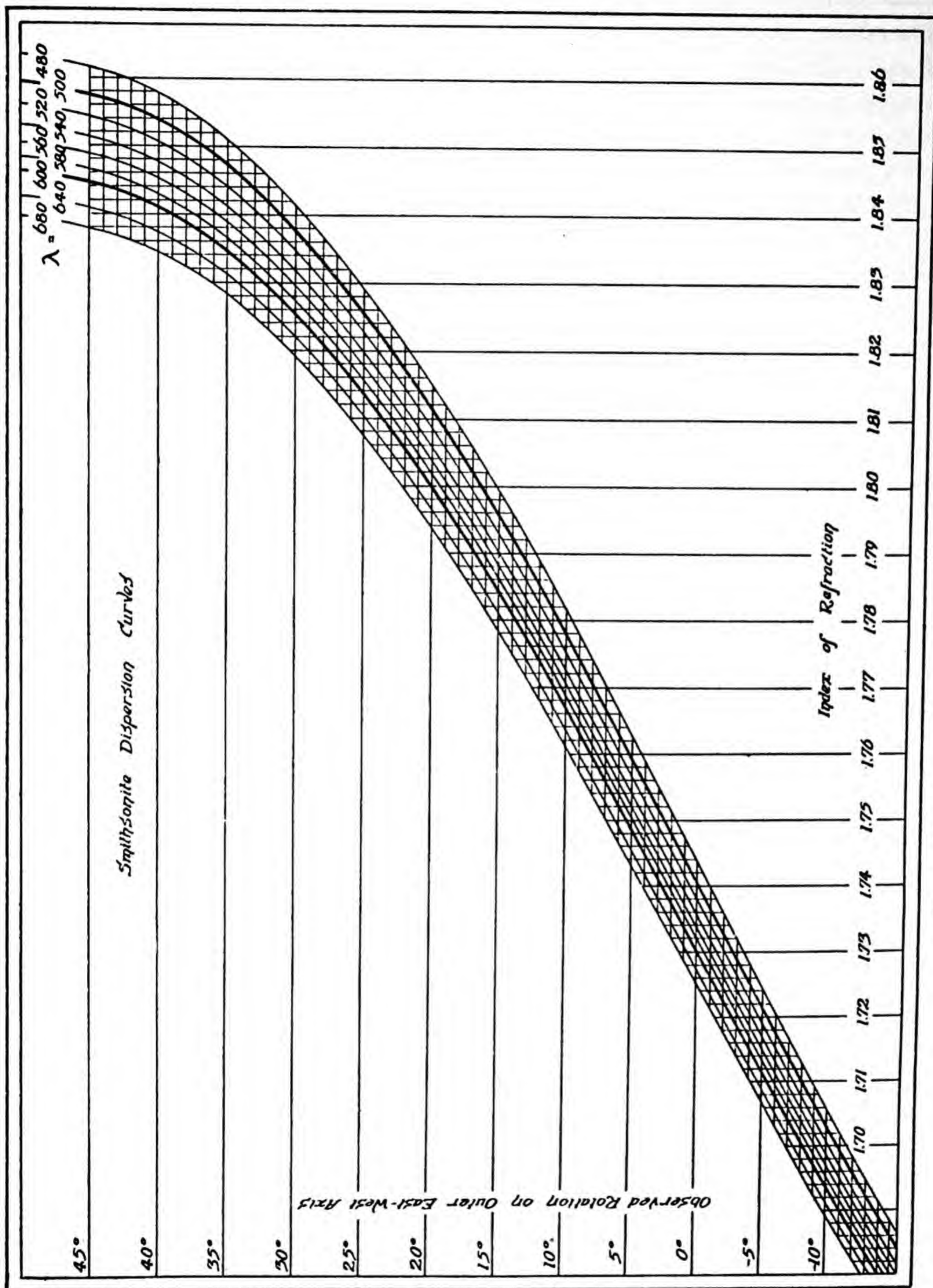
FIGURE 90.—*Curves for smithsonite refractometer*

For various wave lengths of light, plotted against the refractive index. The ordinate scale is given in terms of the graduations on the outer east-west axis of the universal stage. A similar graph for calcite used with this chart provides a means of measuring any refractive index of liquid in the ordinary range of common minerals.

The chart is used as follows: On a slide which carries a smithsonite crystal place a drop of liquid, the index of which is sought. Rotate the mount in the principal section to make the crystal and liquid agree in refractive index, in monochromatic light. Then using the reading so obtained on the outer east-west axis, find the intersection of this ordinate value with the wavelength curve of the light used—the abscissa gives the refractive index.

close enough to the recorded values of pure materials so that these curves may be used with an accuracy of about ±.01. However, in making a mount of a cleavage rhomb the fragment will probably not fall truly on the cleavage face, and therefore the curves will not fit accurately a given mount. Therefore, in applying the empirical reading of the outer east-west axis to these curves a correction is necessary, and this correction is applied to all subsequent readings. For steep inclinations this correction is theoretically not sound, but the error is negligible. If a series of readings is to be made, a convenient way to apply the correction is by means of the inner east-west axis. Then it may be ignored in all subsequent readings on the outer east-west axis.

The inclination of the inner stage is of course to be corrected for the difference in index between the liquid and the hemispheres. Since the mount is usually made with hemispheres 1.649 this correction has been applied in constructing the curves and need not be considered. The only correction required is therefore that described above for failure of the crystal to lie on its cleavage face.

The use of the curves on the plate is obvious. The ordinate values are the readings on the outer east-west axis. Follow the reading obtained to the curve representing the wave length of light used. The abscissa gives the refractive index of the liquid.

The accuracy of refractive index readings by this method is ±.001 when properly executed. Care must be taken to center the illumination with the Bertrand lens when the inner stage is horizontal before making a reading with monochromatic light. The same precautions should be taken in controlling the temperature of the mount as are taken with any universal stage mount. The temperature factor need not be considered when using the curves of the plate since it is usually required only that the mount be at the same temperature as the mount of the unknown mineral being studied on a companion microscope.

In the writer's laboratory this technique is sometimes used in the double-variation procedure, substituting a second universal stage mounted with smithsonite, as described here, in place of a high index Abbé refractometer. A high-index Abbé refractometer is to be preferred on account of its greater accuracy. Since high-index work is usually secondary to work below 1.70 in most laboratories, this is offered as an economy measure where a larger return may be expected from an additional universal stage rather than from a high-index refractometer.

Chapter 12

Special Applications of the Universal Stage

(1) The identification of calcite and dolomite in thin section.

FOR certain purposes it is desirable to distinguish these two carbonates in thin section, and attempts have been made to develop a method. Some methods are successful but laborious since they involve removal of the cover glass and the application of reagents. The method described here is based on an approximate measure of the refractive index.

The cementing medium usually used in making thin sections is Canada balsam, which has a refractive index of about 1.54 when properly hardened. This value falls between ω and ε for calcite and dolomite and may therefore be used as a measure of these indices where balsam comes in contact with these crystals in thin section. The borders of a thin section afford such a place of contact, and cracks in the mount, commonly present, also may be used since the balsam cement fills these cracks. Since the universal stage makes various orientations possible we may find that orientation in which the refractive index of the carbonate agrees with the index of the balsam. The orientation is then a clue to the identity of the crystal. The procedure follows:

Choose a crystal that is in contact with balsam and orient it, preferably with the optic axis horizontal. Rotate on the outer vertical axis 90° if necessary (which it usually is) to make the principal section north-south. The transmitted ray now has the index of ε, which may be changed by a rotation on the outer east-west axis from ε toward ω. As this rotation is made observe the Becke line and stop when the index of the crystal agrees with that of the balsam. Read the rotation on the outer east-west axis. This value is different for the two carbonates.

Reference to Plate 10b indicates that a rotation of 36° (white light = 35.5°, Na = 36.2°) is required to change the index of the transmitted ray of calcite from $\varepsilon = 1.486$, to $\varepsilon' = 1.54$.[9] Also a rotation of 29.5° changes the index of the transmitted ray of dolomite from $\varepsilon = 1.50$, to $\varepsilon' = 1.54$. If the hemispheres 1.516 are used the correction for difference in index between the crystal and hemispheres

---

[9] In calcite $\omega - \varepsilon = 0.172$Na. This is an ordinate and abscissa value in Plate 10b. ε' 1.54 $- \varepsilon$ 1.486 = 0.054. This is an abscissa value since we are increasing the index. The intersection of the abscissa value (0.054) with the inclined line from 0.172 gives the rotation value 36.4°. The correction is small, $-0.2°$.

is negligible for the purpose, and the direct readings may be used. The rotation on the outer east-west axis will be one of these two values if the crystal is calcite or dolomite. The rotation for magnesite ($\varepsilon = 1.51$) is $25.5°$.
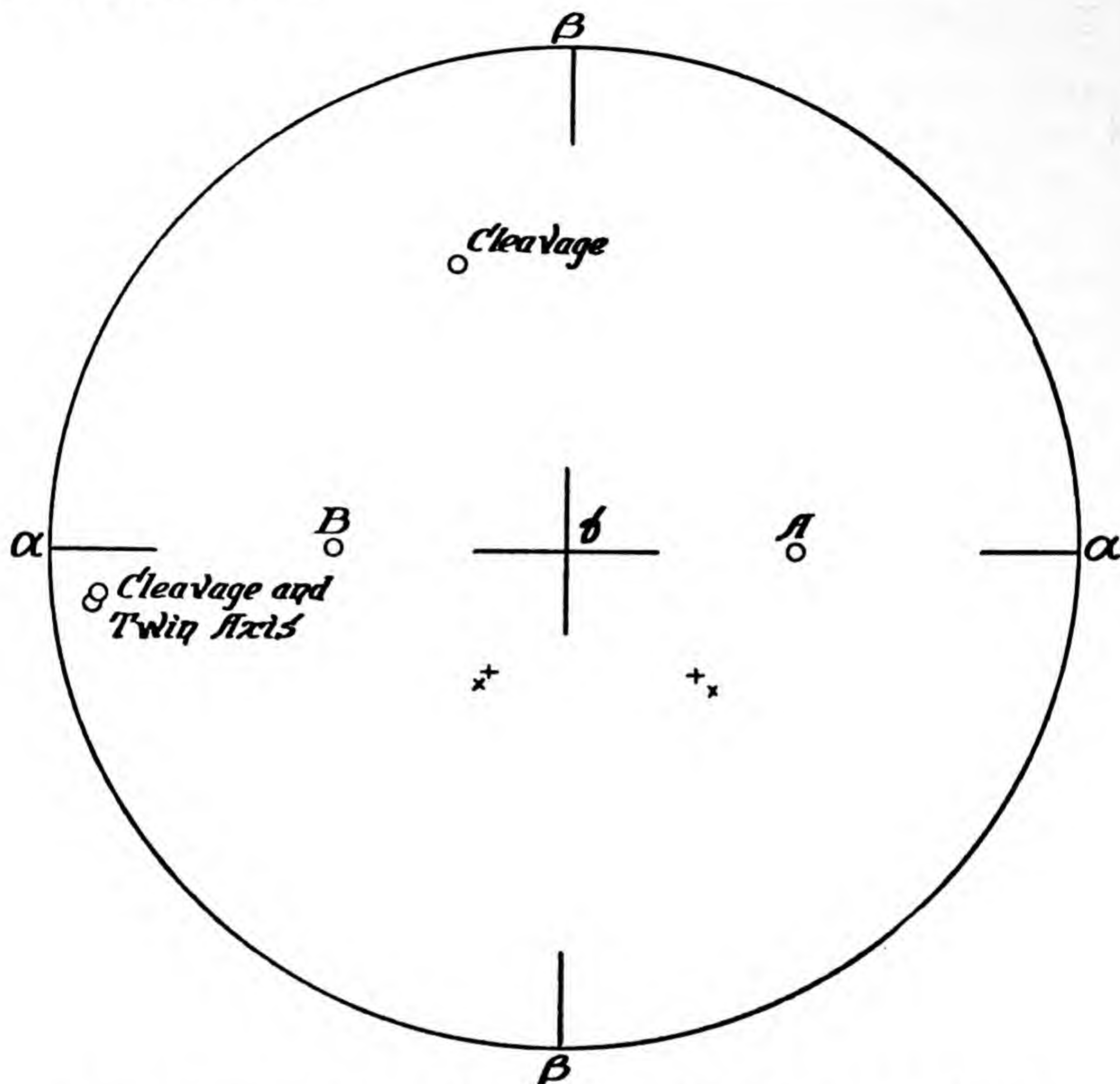

FIGURE 91.—*Stereogram of cyanite crystal in Figure 1 of Plate 7*
Plotted with the optical directions in cardinal orientation (Table 24).

If carbonates of higher indices are to be determined by this method another cementing medium may be used such as piperine ($n = 1.68$) or any of the other higher-index media.

(2) To determine the relationship between the optical and crystallographic elements of a given crystal.

It is required occasionally to relate the optical properties to the crystal axes, either as a determinative aid when other properties are not sufficiently convincing or because of some departure from regularity suggesting that some new feature should be recorded. In triclinic and monoclinic crystals the relationship of optical and crystal-

TABLE 24.—*Twin determination—Modified Fedorow method*

(Figs. 91-93)

Specimen No. *CF5*   Locality *Near Rhinelander, Wis.*   Rock *Cyanite schist*
Zero Values: Mic. *36°*   O. V. *91°*   Mineral *Cyanite*   Comp.
Unit 1:   Twin Laws: *Normal*

I. E-W	29.5° S	
N-S	20.5° W	
O. A. 1	54° E	
2	— —	
	2V-1	2V-2
O. V	(	(
O. E-W		
M	(	(

I. V.	99°
α	E
β	N
γ	⊥
Bx$_a$	E
Sign	(−)
β	
2V	

Comp. Face 1	H	4.5° W
	V	⌐7°
2	H	
	V	(
Cleav. Face 1	H	5° S
	V	⌐85°
2	H	27° N
	V	⌐21°

Remarks:

lographic properties is a most definite and convincing determinative criterion. The results are best expressed in stereographic form which covers the third dimension, but they may also be expressed in orthographic or clinographic form. One example illustrates the method most easily followed.

A cyanite crystal illustrated in Figure 1 of Plate 7 from a cyanite schist in northern Wisconsin is recorded in Table 24. In Figure 91 these data are plotted in stereographic form as the crystal was oriented on the microscope. Two cleavage planes were made vertical and east-west. One composition face was made vertical and north-south. It was tested and found to be a normal twin. The twinning axis is therefore also the pole of (100).

Figure 91 gives all the necessary information, but some prefer to make the crystallographic planes rather than the optical elements the basis of plotting. This usually means for cyanite that the pole of (100) is centered and the c axis is north-south (Figs. 92-93).

Some starting point in the crystallographic properties is necessary, and in this case the two cleavages give us our bearings. Crystal faces may be present. Lacking one of these it may not be possible to solve the problem.

(3) The determination of the refractive index on balsam-filled cleavage cracks (as developed by Nikitin (1936, p. 54)).

This method uses the principle that well-developed cleavage which is dark when nearly vertical (Pl. 7, fig. 7) may become light and

transparent when inclined (Pl. 7, fig. 8). Frequently the reason is that the cleavage cracks are filled with balsam which differs in refractive index from that of the mineral. When the balsam-filled crack is nearly parallel to the axis of the microscope total reflection
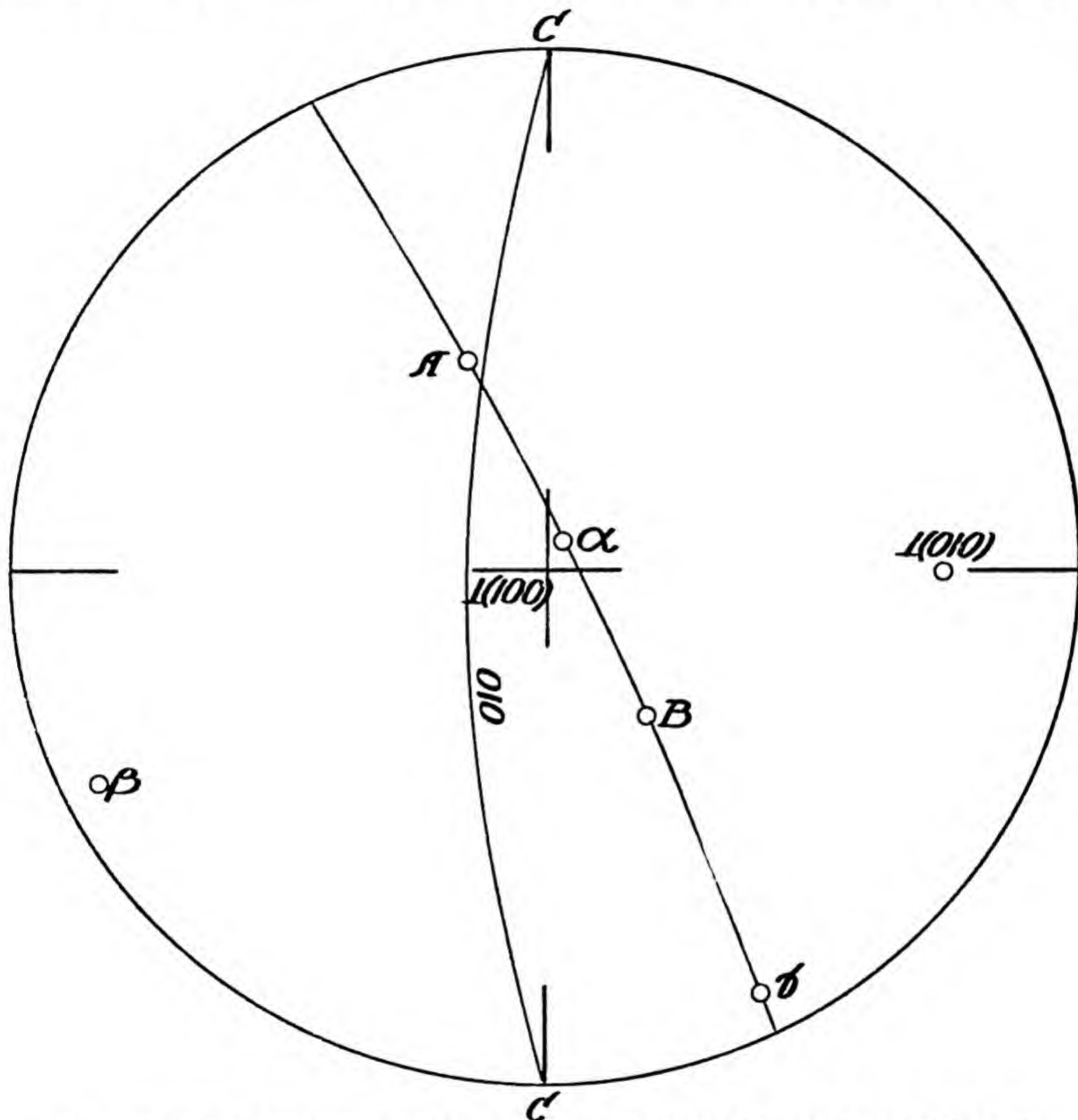

FIGURE 92.—*Stereogram of cyanite crystal in Figure 1 of Plate 7*
Rotated from the optical orientation of Figure 91 to center the pole of (100) and
make the c axis north-south

at the balsam-mineral interface prevents the transmission of light to the eye—hence the cracks appear dark. Sometimes cleavage cracks are dark because of alteration products. This condition differs from balsam filling usually in that the alteration products remain dark on all rotations. However, minerals of very high index may behave similarly since the pertinent angle of total reflection is so small that the stage cannot be inclined steeply enough to reach it. This difficulty is accentuated by the nullifying effect of a high refractive index on any rotation on a horizontal axis. This

is so true that crystallographically wide rotations on a horizontal axis are impossible in minerals of high refractive index.

If the mineral and balsam agree in refractive index the balsam-filled cleavage cracks are never dark, through total reflection. If
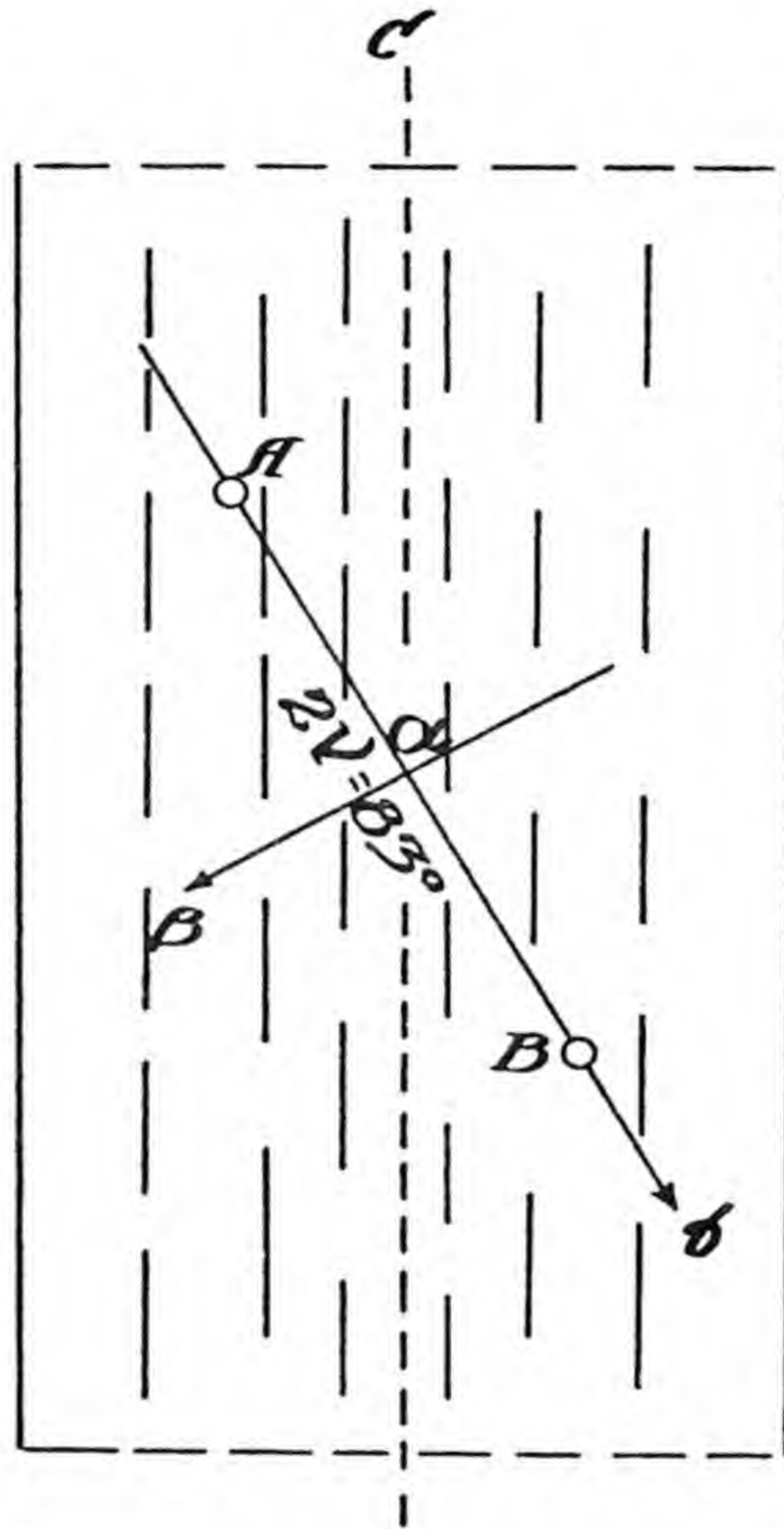

FIGURE 93.—*Orthographic equivalent of Figure 92*

the difference in index between the mineral and balsam is relatively small the cleavage cracks appear dark only when the cleavage cracks make a small angle with the axis of the microscope. The higher (or lower) the index of the mineral the greater the difference in index from that of balsam and the greater may be the angle between the axis of the microscope and the cleavage plane without the cleavage cracks appearing bright. The method then is to measure this angle on a mineral of unknown index and to use this measurement on the accompanying graph as a clue to the index of the mineral (Fig. 94).

In practice the procedure is this: First determine the angle made by the cleavage plane with the normal to the section. To do this make the cleavage trace east-west and rotate on the east-west axis to make the cleavage vertical. Then the angle on the scale of the
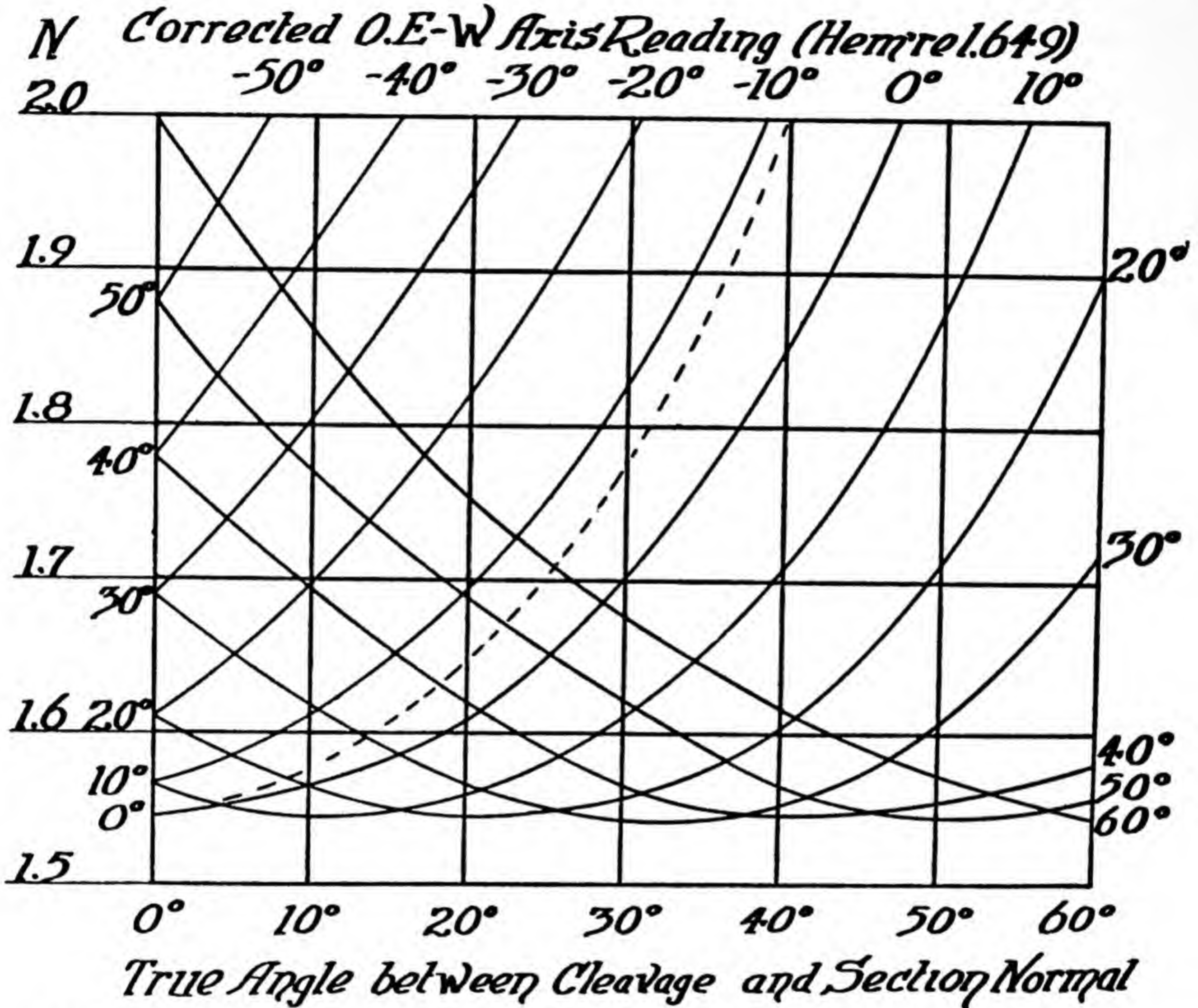

FIGURE 94.—*Nikitin's diagram to determine refractive index from cleavage*

By use of the principle illustrated in Figures 7 and 8 of Plate 7.

Based on data recalculated for use with hemispheres of refractive index N_D 1.649. (Dotted line shows the original 0° curve for use with hemispheres N_D 1.524 for which the diagram was constructed.) Diagram is scaled to read indices as high as 2.0 in the belief that the value of this method of reading higher is doubtful.

east-west axis is the apparent angle sought. (The other horizontal axes are assumed to be set at their zero readings.) The apparent angle is to be corrected for the difference in index between the crystal and the hemispheres. To accomplish this, since the index of the crystal is unknown, the procedure must be followed through twice on the chart. The crystal is now inclined on the same east-west axis to observe the position in which total reflection ceases.

The values are used on the chart (Fig. 94) as follows: The first angle read—that between the cleavage and the normal to the section— is found on the abscissa. The second angle—at which total reflection

ceases—is found on the curves or by interpolation between them. The refractive index is found on the ordinate scale. After doing this once, the first angle is then corrected on Plate 8 and the chart is used again. The second value is final.

In making the two angle readings notice whether the second rotation on the east-west axis is in the same or the opposite direction as the first. If in the same direction then the curves which carry a positive sign are used, and *vice versa*.

Nikitin claims little accuracy for the method. However, as pointed out in Chapter 10, any method which reveals the general region of the refractive index of high index crystals is of value. The outstanding difficulty is that the "point" at which total reflection ceases is a range, which Nikitin gives as 7°-12° according to the quality of the cleavage. He claims greater accuracy if the crystal permits rotation to the end point of total reflection, in two directions instead of one, thereby yielding an average of two readings.

Nikitin's original chart was calculated for hemispheres 1.524 in refractive index. It is recalculated in Figure 94 for hemispheres 1.649 because the main value lies in determining crystals of high refractive index, in which case high index hemispheres would ordinarily be used. The dotted-line curve is Nikitin's 0° curve for hemispheres 1.524. The highest index reading given in the chart reproduced here is 2.0. In its original form the chart reads to 3.6. The value of data of this nature for crystals of index above 2.0 is very doubtful indeed.

Better results can be had if attention is limited to one part of one cleavage plane for one set of readings. In the hornblende crystal pictured in Plate 7 the photomicrographs were made at angle readings on the outer east-west axis which are respectively 16°S and 29°S. This was done to bring out adequate contrast in the illustration. In the actual determination however the values 21°S and 23°S were the chosen end points for the range, and the average is 22°S. The cleavage was made vertical at 5° N. This value is so small that no correction is needed. These values applied on the chart give a refractive index of 1.68.

(4) The measurement of the refractive index on the universal stage by means of a double hemisphere.

This has been developed by E. Leitz, Inc., who also manufacture the accessories needed for the purpose. The method is based on the principle of the crystal refractometer and like the crystal re-

fractometer it has, theoretically, no upper limit. Unlike the crystal refractometer it has no lower limit since the calibrated glass plate which is affixed to the plane surface of the double hemisphere is air backed.
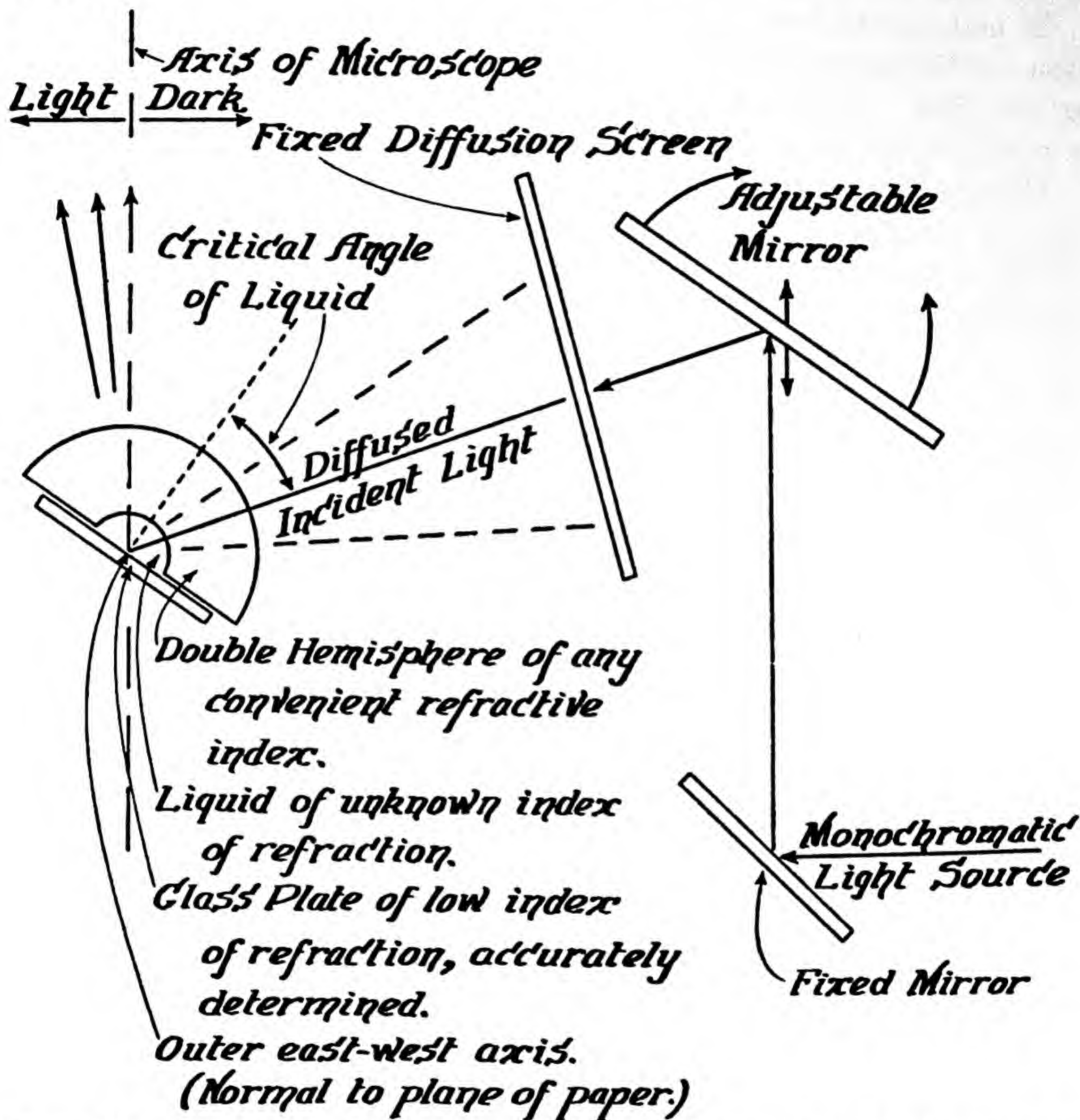

FIGURE 95.—*Diagrammatic scheme of double hemisphere method of refractometry* For measuring the refractive index of liquids. This is a convenient and desirable method for measuring the refractive indices of liquids of high index. (E. Leitz, Inc.)

The essential accessories (Fig. 95) are (1) the double hemisphere, which is a glass hemisphere in which is ground a hemispherical cavity large enough to hold a few drops of liquid. The two hemispherical surfaces have a common center which is also to be adjusted to lie in the outer east-west axis. After filling the hemispherical cavity with liquid, seal it with (2) a glass disc of known refractive index. This mount is then placed on the universal stage on the

microscope and illuminated from directly in front, with monochromatic light. To facilitate reading, the incident light should pass through (3) a diffusing screen to scatter the incident light enough that the incident cone will include the critical ray.

To facilitate readings, some arrangement is desirable to make possible the adjustment of the angle of incidence, since results are best when there is ample incident light at the critical angle of the liquid. This angle is smaller for liquids of higher refractive indices requiring a higher point of origin. A simple arrangement for the purpose is an adjustable mirror which can be mounted on a ring stand (Fig. 95).

The manufacturer recommends the use of a special ocular and objective and the use of the Bertrand lens. He provides a table which translates rotation values on the east-west axis into refractive indices.

The accuracy claimed for the method is $\pm.002$ for a refractive index of 1.80.

Form 1.—*Double variation data*

MINERAL LABORATORY

Mineral...Locality...

	I. E–W			Orientation: α	
	N–S			β	
	O. A. 1			γ	
	2			I. V.	
		2V–1	2V–2	Immersion Liquid	
	O. V.	(	(	Hemispheres	
	O. E–W			Zero Values: Mic	
	M	(	(	O. V	
	2V				

Ray	T.1	T.2	λ	Ref.	Cor.	Index	Rot'n	From	Diff.	λ	Ad. Cor.	Ray # 3

FORM 2.—*Twin determination—Modified Fedorow method*

Specimen No. ..   Locality ....   Rock ....

Zero Values: Mic. ..   O.V   Mineral ..   Comp. ....

Unit 1:   Twin Laws:

I. E–W			I. V.		Comp. Face 1	H	
N–S			α			V	(
O. A. 1			β			H	
2			γ		2	V	(
	2V–1	2V–2	Bxa		Cleav. Face 1	H	
O. V	(	(	Sign			V	(
O. E–W			β			H	
M	(	(	2V		2	V	(

Unit 2:

I. E–W			I. V.		Comp. Face 1	H	
N–S			α			V	(
O. A. 1			β			H	
2			γ		2	V	(
	2V–1	2V–2	Bxa		Cleav. Face 1	H	
O. V	(	(	Sign			V	(
O. E–W			β			H	
M	(	(	2V		2	V	(

Unit 3:

I. E–W			I. V.		Comp. Face 1	H	
N–S			α			V	(
O. A. 1			β			H	
2			γ		2	V	(
	2V–1	2V–2	Bxa		Cleav. Face 1	H	
O. V	(	(	Sign			V	(
O. E–W			β			H	
M	(	(	2V		2	V	(

Unit 4:

I. E–W			I. V.		Comp. Face 1	H	
N–S			α			V	(
O. A. 1			β			H	
2			γ		2	V	(
	2V–1	2V–2	Bxa		Cleav. Face 1	H	
O. V	(	(	Sign			V	(
O. E–W			β			H	
M	(	(	2V		2	V	(

Remarks:

FORM 3.—*Twin determination*

Reference Data

page- —

Unit- ———

to Unit- ———
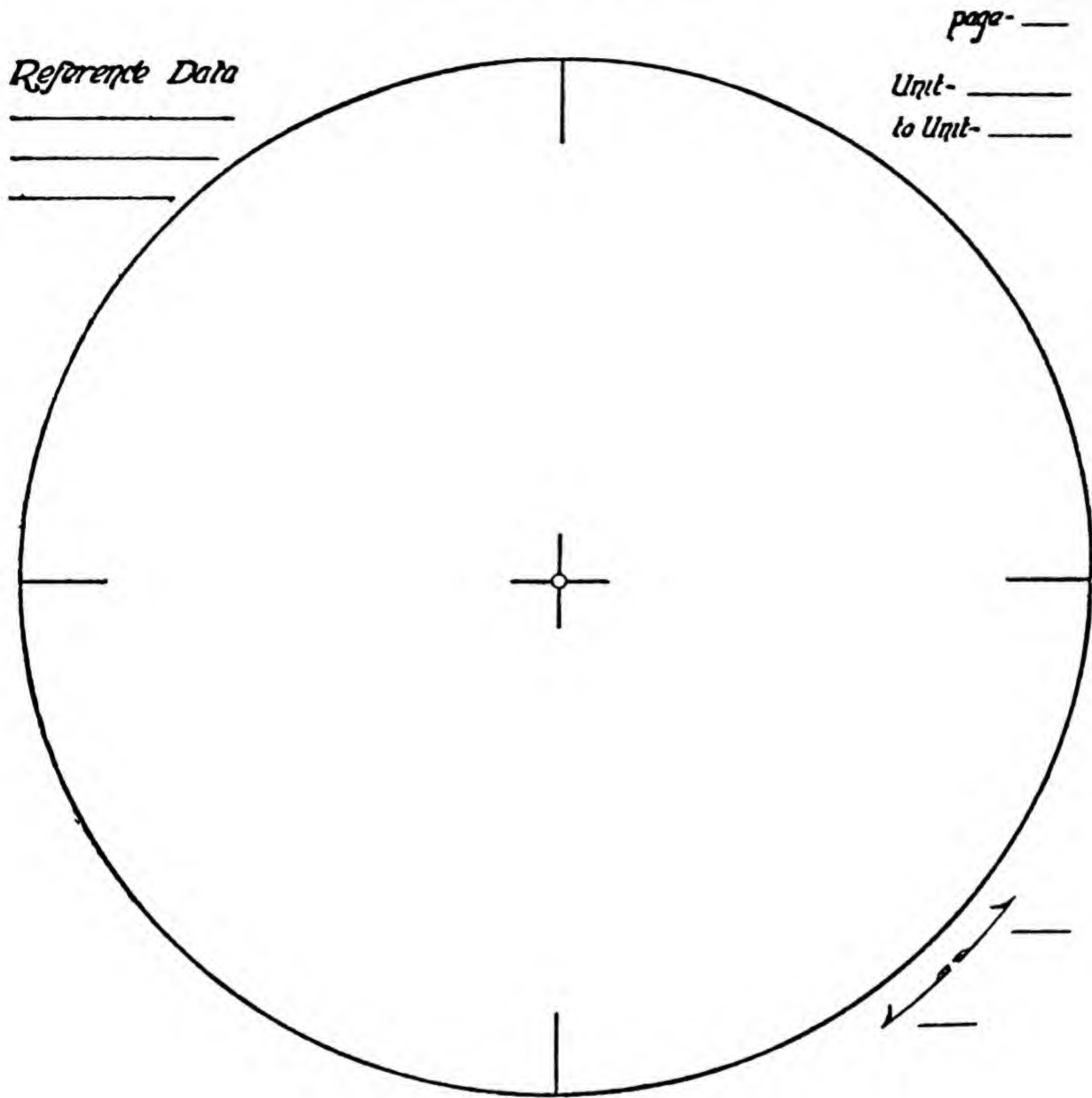
FORM 4.—*Twin determination—Five axis method*

Reference Data:
Zero Values: Mic.....   O. V. ....

Unit 1:

1. E–W	
N–S	
O. A. 1	
2	
2V: —	
O. V	(
O. E–W	
M	(

I. V.	
α	
β	
γ	
Bxₐ	
Sign	
β	
2V	

Comp. Face 1.	O. V.		
	N–S		
	I. E–W		
Twin Axes (O. E–W)			

Comp. Face 2.	O. V.		
	N–S		
	I. E–W		
Twin Axes (O. E–W)			

Remarks:

FORM 5.—*Birefringence determination*

Zero Values: Microscope Stage　　　O. V. Axis
Sample Data　　　　　　　Hemispheres
Bif. =　　　　Mineral　　　　　　　　　　　　　　　　　　　　Quartz:

I. E–W	
N–S	
O. A. 1	
2	

	2V–1	2V–2
O. V	(	(
O. E–W		
M	(	(
2V		

Bx to O. A	
V–Cor't'd	
O. A to Com	
Rot Cor	
Comp Sign	
Ber. C	
Ret	
M′ at C	

O. A.	
Cor.	
Comp ∠	
Cor.	
Rot.	
Ber. C	
Ret.	
M′ at C	
M	

Bif. =　　　　Mineral　　　　　　　　　　　　　　　　　　　　Quartz:

I. E–W	
N–S	
O. A. 1	
2	

	2V–1	2V–2
O. V	(	(
O. E–W		
M	(	(
2V		

Bx to O. A.	
V–Cor't'd	
O. A to Com	
Rot Cor	
Comp Sign	
Ber. C	
Ret'n	
M′ at C	

O. A.	
Cor.	
Comp ∠	
Cor.	
Rot.	
Ber. C	
Ret.	
M′ at C	
M	

Bif. =　　　　Mineral　　　　　　　　　　　　　　　　　　　　Quartz:

I. E–W	
N–S	
O. A. 1	
2	

	2V–1	2V–2
O. V	(	(
O. E–W		
M	(	(
2V		

Bx to O. A.	
V–Cor't'd	
O. A to Com	
Rot. Cor	
Comp Sign	
Ber. C	
Ret'n	
M′ at C	

O. A.	
Cor.	
Comp ∠	
Cor.	
Rot.	
Ber. C	
Ret.	
M′ at C	
M	

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